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An investigation of the effects of shear on the compressive strength of plating

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Massachusetts Institute of Technology

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AN INVESTIGATION OF THE EFFECTS OF SHEAR ON THE COMPRESSIVE STRENGTH OF PLATING

JOHN A. BALLARD, JR.
BERNARD C. LENNON

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May 20, 1949

Professor J. S. Newell,
Secretary of the Faculty,
Massachusetts Institute of Technology,
Cambridge, Massachusetts.

Dear Sir:

In accordance with the requirements for the Degree of Naval Engineer, we submit herewith a thesis entitled "An Investigation of the Effects of Shear on the Compressive Strength of Plating".

Respectfully,

AN INVESTIGATION OF THE EFFECTS OF SHEAR ON THE COMPRESSIVE STRENGTH OF PLATING

By

John A. Ballard, Jr.
Lieutenant, U.S.Navy
B.S., U.S. Naval
Academy, 1943

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Lieutenant, U.S.Navy
B.S., U.S.Naval
Academy, 1942

Submitted in partial fulfillment of the
requirements for the degree of
NAVAL ENGINEER
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
1949

ACKNOWLEDGEMENT

The authors wish to express their sincere appreciation and indebtedness to Professor Charles H. Norris for the suggestion of the apparatus and for guidance during the investigation.

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SUMMARY

Results

The testing apparatus constructed was successfully utilized in applying a compressive force and a shearing force to a plane, unstiffened, rectangular panel. Under combined conditions of loading, it was found that shear reduced the stability of a panel in compression.

Object

The purpose of this investigation was to design, construct, and test a device which was to be capable of applying a compressive force and a shearing force to a plane panel of plate. This device was then to be used to determine the combined effect of shear and compression on a panel of plate of a length-to-width ratio corresponding to the representative ratio of plating dimensions most often found in ship construction.

Procedure

The strain at the center of a plane, unstiffened panel was measured by strain gauges. The panel was compressed in a direction parallel to its longer sides and subjected to a shearing force applied in a diagonal direction which was further resolved into components along the four panel edges by a system of linkages. Measurement of compressive load was made by a balance scale and of shearing force by strain gauges located in the diagonal shear load apparatus.

Conclusions

It is possible to attain the combined condition of loading in the panel with this apparatus. Difficulty is encountered in attempting to duplicate test results using other specimens. Improper functioning of the apparatus and inconsistencies in assembly have caused erratic strain readings in the specimens tested.

Recommendations

Consistent results may be obtained from the apparatus if the components are very accurately machined and assembled. Modifications made on the present arrangements to insure that the specimen is unstiffened, freely supported, and subjected to a more uniform distribution of shearing force will facilitate further investigation.

INTRODUCTION

The application of the theories of elasticity and strength of materials to the structural design of ships has increased considerably in recent years. Limitations have been imposed upon the direct application of these theories for several reasons. The most important limitations are, first, that the structural members may be subjected to combined loading for which the theories may not apply, and, second, that the action of the members is governed by the method of assembly, degree of edge fixity, and the influence of adjoining structural members.

To insure that the most satisfactory structure will be obtained, it may frequently be advisable to verify experimentally the theoretical solution for the required design. An experimental analysis will, in many cases, indicate the efficiency and safety of the structure, and, in addition, may lead to a possible saving of weight, which is very important in ship design.

Several experimental investigations have been conducted on the compression of rectangular plates and on the buckling of plates under shearing forces. In 1937, Palmer and Pfingsteg (4) made an experimental and theoretical investigation of the effect of end fixity on the strength of plating in compression. Reports of the United States Experimental Model Basin, the David Taylor Model Basin, and the National Advisory Committee for Aeronautics describe

experimental investigations conducted on stiffened and unstiffened plates under varying conditions and types of loading. A brief description of typical experiments on the buckling of plates is presented by Timoshenko (1).

An important condition existing in the side shell, decks, and bulkheads of a ship is the combined application of direct and shear stresses due to the working of the ship in a seaway, the condition of loading, or some other cause. The more serious condition is that of combined compression and shear. It has been suggested in (2) that an experimental investigation be made of the effect of shear on the compressive strength of plating. This suggestion has been accepted as the objective of this report.

In the field of aeronautics, an investigation of this combined condition of loading has recently been completed. The test specimen utilized in this report (5) consisted of a long, rectangular plate divided into a large number of rectangular panels by stiffeners spaced at regular intervals. The compressive force was applied in a direction parallel to the shorter edges of the panel, while, usually, because of the longitudinal arrangement of plating, in a ship the compressive force is applied parallel to the longer edges. The testing apparatus of this report (5) was designed in such a manner that a variation in degree of edge fixity along the longitudinal

edges of the panels could be obtained. Longitudinal, lateral and shear strains were measured and the shape of the buckled plate was determined by means of profile and slope recordings. From this data the stress distribution in the plate was computed.

The testing device used in the report briefly described above served, to a limited extent, as a guide in the design of the testing apparatus used for the present investigation. In view of the limited time available and in order to simplify the problems of construction and testing, the apparatus was designed to accommodate a single, unstiffened, flat, rectangular panel. Inasmuch as a riveted plate is considered to be freely supported, i.e. change of slope at the edges is permitted but deflection is prevented, the test specimen was held on all four edges by small bolts. The various specimens tested were subjected to pure compression tests followed by combined application of compression and shear forces. In a few instances, the specimen was subjected to a shear force only. No effort was made to determine the distribution of stress in the panel, the object being simply to determine under what combination and magnitude of loading the buckling of the specimen would occur.

PROCEDURE

The experimental work involved in this investigation consists of two distinct parts which it would be well to clearly define at the outset. First, there is the design, construction and assembly of the testing apparatus. Second, there is the actual testing of the plate specimens under variable conditions both of the compressive load and of the shearing load. It is the first of these two phases on which the major portion of the time and effort has been spent.

The manner of applying the compressive load to the plate specimen consists of two similar framework structures which are referred to herein as the end frames. The specimen is supported in a horizontal plane between the topmost bar of each of the end frames by steel plate members, which are welded to sections of pipe of such inner diameter that they will slide over the topmost bars of the end frames. The topmost bars of the end frames are themselves sections of steel pipe having a proper outside diameter to permit a loose fit between the two sections of pipe. A horizontal axis is established vertically below the topmost bar to permit rotation of the end frame in a vertical plane about this lower horizontal bar. At the outer end of the end frame, measured horizontally from the lower bar, a flat steel plate is welded in a horizontal position. On one of the end frames a vertical

PROCEDURE

The experimental work conducted in this investiga-tion consists of two distinct operations [illegible] as well as already [illegible] [illegible]. First, there is the design, construction and assembly of the testing ap-paratus. Second, there is the actual testing of the plate specimens under various conditions [illegible] of the compressive load and of the shearing loads. It is the first of these two phases to which the major portion of the time and effort was [illegible].

The method of applying the compressive load to the plate specimens consisted of two [illegible] framework struc-tures which are [illegible] to [illegible] on the test frames. The specimen is supported in a horizontal plane between the flanges [illegible] of each of the two [illegible] by steel plate members, which are welded to [illegible] of each [illegible] [illegible] that they will [illegible] the [illegible] of the test frames. The [illegible] ends of the test frames are themselves [illegible] [illegible] outside [illegible] to permit a [illegible] the [illegible] the two of these. A horizontal axis is [illegible] [illegible] below the [illegible] to permit rotation of the test frames in a vertical plane about this lower horizontal bar. At the outer end of the test frames, [illegible] from the lower bar, a flat steel plate is welded in a horizontal position. On top of [illegible] frames a vertical

force from a hydraulic jack is applied to the underside of this flat plate. On the other end frame the forces transmitted through the apparatus exert a load along a line of contact onto the weighing platform of a balance scale located beneath the flat plate of the end frame.

The design of the relative proportions of the end frames is dependent on the moments about the lower bar of the vertical force due to the hydraulic jack and the desired compressive load transmitted into the plate specimen from the upper bar of the end frame. The proportions of the end frame on the scale side are similarly dependent on the load transmitted to the scale. The proportions adopted make it possible to apply a 4000 lb. compressive load to the plate specimen.

Having established the magnitude of the available force from the compression testing apparatus the selection of the type of material and the size of the plate to be used for the specimen remained to be determined. From the survey of previous investigations it was evident that aluminum was the most desirable material for laboratory work. It required further study into the properties of the various types of aluminum to reach a decision as to the type which best represented the behavior of structural steel.

The dimensions of the plate specimen were arrived at by a study of side shell and both transverse and longi-

tudinal bulkhead plans for various types and sizes of ships. The length-width ratio of 3.5 to 1 selected from this study, represents the average ratio for plate panels used in ship construction. Using this length-width ratio, calculations were made for the critical compressive stress for a purely compressive condition; and for the critical shearing stress for a pure shear condition. These calculations were made on the basis of the plate being freely supported on four edges, first under uniform compression, and second when submitted to the action of a uniform shear. The relations used and the constant factors associated with them were taken from reference (3). The critical values were determined for plate widths of four, five, and six inches and for plate thicknesses ranging from 0.025 to 0.070 inches. The results of these critical values revealed, that a force to produce the shear is on the order of five times that force required to produce the compression in the same plate. With the aim at attaining the smallest of these required shearing forces, the plate width was chosen as six inches.

The manner of applying a force to the plate so that uniform shear stress exists at any edge presented the most difficult problem. A force applied along a diagonal of the plate specimen may be resolved into two components parallel to each of the edges of the plate. These components are proportional to the dimensions of the length

and width of the plate. The searing area of the plates edges is likewise proportional to the dimensions of the length and width for a given plate thickness. Thus when a force is applied along the diagonal, its components along the length and width of the plate are so proportioned as to cause an equal shear stress to exist along all four edges of the plate.

To introduce the shearing force by pulling from each of two diagonal corners a parallelogram linkage system has been employed. This system consists of a solid flat steel plate, referred to as the lever plate, to which are attached flat steel strips called linkage bars. The other ends of the linkage bars are attached to the respective edges of the plate. Along the ends of the plate, these linkage bars are bolted to the end compression attachments by a single bolt. This permits relative movement between the linkage and the compression attachment. This is necessary since the end compression attachment is only free to move along the axis of the upper bar of the end frame.

For the connection between the linkage bars and the sides of the plate, that is the long dimension of the plate, again a single pin is used to permit relative movement of the parts. In this case however the shearing force is further distributed by three additional pins, each transmitting one fourth of the shearing force to the

plate. Each pin is connected to the other by a flat metal strip on top and bottom of the plate, so positioned along the length of the pin from the center of the plate, and of such cross sectional area that the required amount of shearing force will be carried into the plate.

The first approach to this problem was made by attempting to transmit the shearing load to the sides of the plate through the lateral supports. This was later abandoned in favor of the method just described. The lateral supports thus serving only the single purpose of supporting the plate when subjected to a compressive load. The holes through these lateral supports for the four pins distributing the shearing load were drilled over size, thus preventing the lateral supports from contributing anything toward the application of the shearing force.

A modification to the four pin shear distribution linkage system was attempted in the final stages of the investigation. This procedure employed only the two farthermost pins on either side for transmitting the shear force to the plate specimen.

The magnitude of the shearing force to be applied to the plate in the direction of its diagonal has already been pointed out as being relatively large. In order to attain the proper magnitude as well as direction

along the diagonal a wire rope is attached to the corner of the lever plate at the two diagonally opposite corners of the plate. This wire rope is in one continuous piece, being looped around a sheave at either end of the testing apparatus. The sheaves are mounted on shafts which are supported by the flanges of an I-beam, which beam extends horizontally above the entire testing apparatus and in line with the diagonal of the plate. At the center of, and mounted above, the I-beam is a device for pulling vertically upward on the wire rope, which as has been stated, is in one continuous piece, either end being attached to one corner of the parallelogram system at each of two diagonally opposite corners of the plate. The upward motion of this jack screw, located at the center of the I-beam, exerts a vertical force which is the vertical component of the tensile pull in the wire rope. A means of close control on the magnitude of the shearing force is thereby attained.

An additional attachment inserted in the line of action of the wire rope is a device which serves a combined purpose. One purpose is to act as a turnbuckle to remove the initial slack from the system. The second purpose is to provide a means of determining the magnitude of the force in the wire rope. An SR-4 strain gauge is attached to either side of the center shaft on the flat areas milled

for the purpose, and measures the strain whenever a pull is exerted on the wire rope. The cross sectional area of the shaft is known and thus affords a means of calculating the tensile force.

The two systems acting on the plate in this investigation act independently of each other as regards the external application of the respective compressive and shearing loads. The only place within the system wherein the two independent forces are joined is in the plate specimen. This interrelation of the combined action is the object of the present study.

The assembly of the testing apparatus completes the first part of the work. The second and most important phase of the investigation is the testing of the plate specimens. The lack of time prevented carrying this portion of the work to the point where sufficient data was obtained from which to determine complete results. Only sufficient information has been compiled to convince the authors that the designed apparatus successfully performs the sought-for relationship. In the course of this investigation approximately eighty test runs were made of which only thirty four were considered of value. The data from these runs is compiled in Appendix C.

The proposed testing procedure was to have been as follows. Each of three thicknesses of plate specimens were to be tested for pure compression and then for pure

shear to determine the critical buckling load for these two conditions independently. Having obtained these critical values the range of the experimentation would have been established. The next step is to test each plate under combined loading conditions by introducing a measured shearing force, and maintaining this force constant while applying increments of a compressive load. The critical buckling load which results will vary dependent on the load combinations. A plot of the ratio of the required compressive load for combined loading to the critical buckling load for pure compression, vs the ratio of the constantly applied shearing load to the critical buckling load for pure shear, will present a graphic picture of the effects sought in this investigation.

For a detailed description of the testing apparatus see Appendix A.

RESULTS

Table I

Plate Specimen No. 1 Plate thickness 0.039 inches

Run No.	Type Test	Observed Critical Buckling Load (lbs)
1	Pure Compression	360
2	Pure Compression	500
3	Pure Compression	480
4	Pure Compression	580
5	Pure Compression	560

Table II

Plate Specimen No. 2 Plate thickness 0.033 inches

Run No.	Type Test	Average Shear Force (lbs)	Observed Critical Buckling Load (lbs)
6	Pure Compression		450
7	Pure Shear		1825
8	Combined Compression and Shear	286	420
9	Combined Compression and Shear	635	640
10	Combined Compression and Shear	1015	880

Table III

Plate Specimen No. 3 Plate thickness 0.033 inches

Run No.	Type Test	Average Shear Force (lbs)	Observed Critical Buckling Load (lbs)
11	Pure Compression		288
12	Pure Compression		290
13	Pure Shear		290
14	Combined Compression and Shear	27	230
15	Combined Compression and Shear	118	160
16	Combined Compression and Shear	246	60

Table IV

Plate Specimen No. 4 Plate thickness 0.0395 inches

Run No.	Type Test	Average Shear Force (lbs)	Observed Critical Buckling Load (lbs)
17	Pure Compression		280
18	Combined Compression and Shear	191	112
19	Combined Compression and Shear	392	176
20	Combined Compression and Shear	630	200
21	Combined Compression and Shear	875	320

10416

Table V

Plate Specimen No. 5 Plate thickness 0.064 inches

Run No.	Type Test	Average Shear Force (lbs)	Observed Critical Buckling Load (lbs)
22	Pure Compression		1320
23	Combined Compression and Shear	474	1300
24	Combined Compression and Shear	1010	1075
25	Combined Compression and Shear	1660	800

Table VI

Plate Specimen No. 6 Plate thickness 0.065 inches

Run No.	Type Test	Average Shear Force (lbs)	Observed Critical Buckling Load (lbs)
26	Pure Compression		1240
27	Combined Compression and Shear	474	1200
28	Combined Compression and Shear	1067	1180
29	Combined Compression and Shear	530	1200
30	Combined Compression and Shear	1110	1000

Table VII

Plate Specimen No. 7   Plate thickness 0.030 inches

Run No.	Type Test	Average Shear Force (lbs)	Observed Critical Buckling Load (lbs)
31	Pure Compression		216
32	Pure Compression		216
33	Combined Compression and Shear	19	180
34	Combined Compression and Shear	57	216

RESULTS

(1) The testing apparatus successfully introduced a compressive load, which caused the specimens to buckle in pure compression at values approximating the theoretical critical values of stress for the design conditions.

(2) The apparatus which applied the shear force to the specimens gave inconsistent results.

(3) The introduction of both a compression load and a sheer force to the specimens caused variations in the critical values of buckling. The majority of the data indicates the stability of the specimen in compression is reduced by shear.

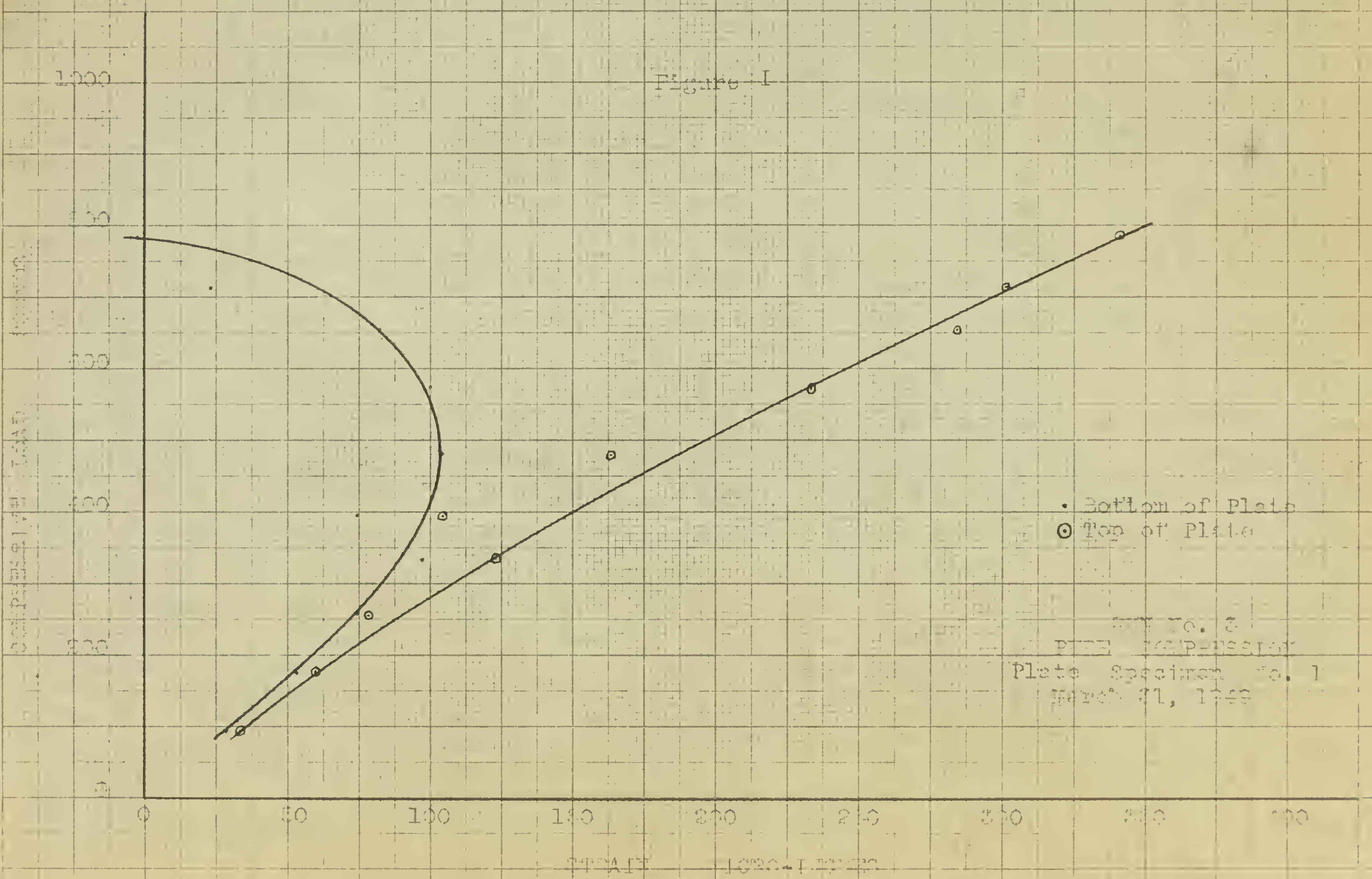


Figure I
1000
0
50
100
· Bottom of Plate
⊙ Top of Plate
Plate Specimen No. 1

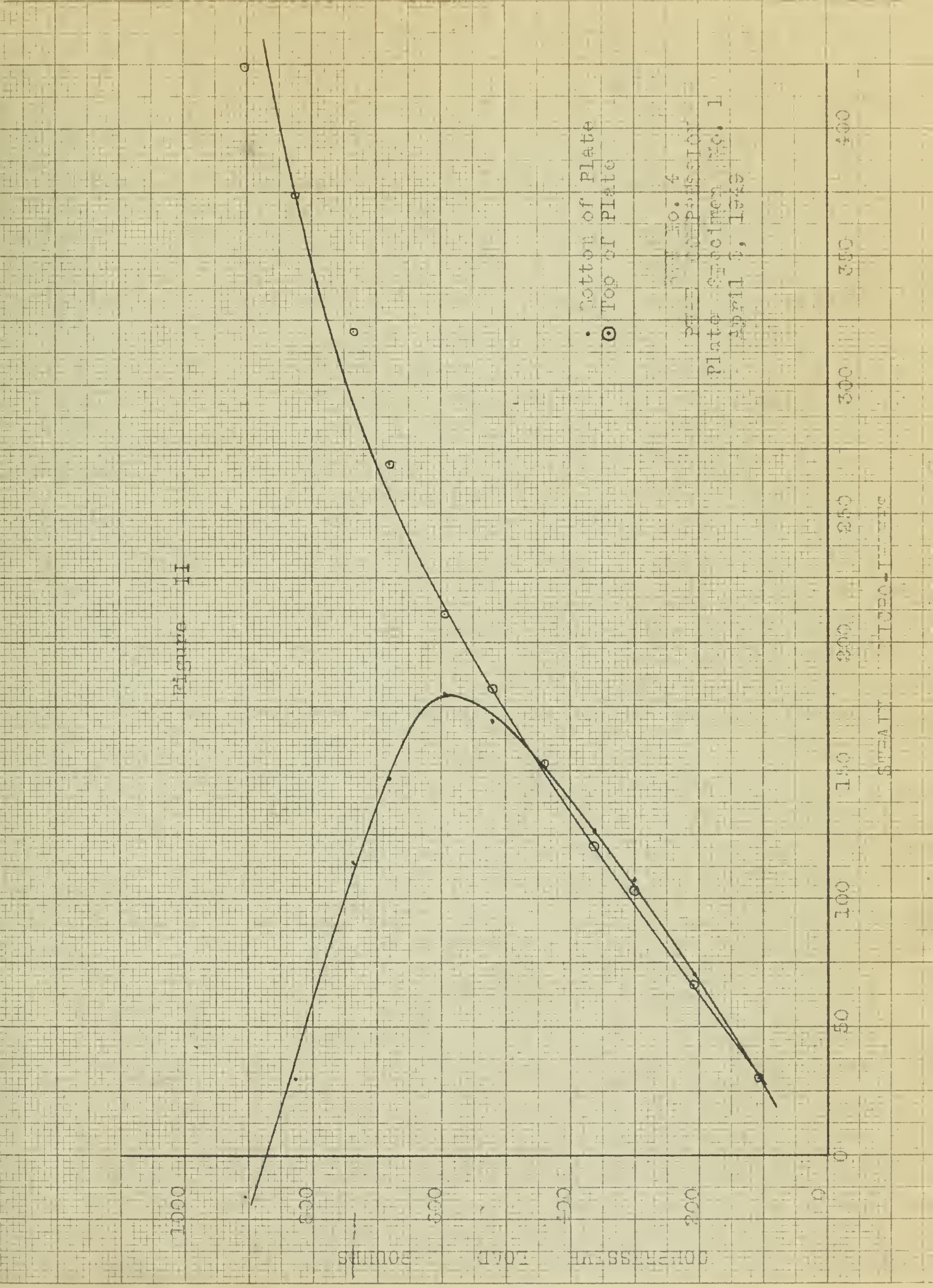


Figure II
Bottom of Plate
Top of Plate
Plate Specimen No. 1
COMPRESSIVE LOAD POUNDS
0
200
400
600
1000
0
50
100
150
200
250
300
350
400

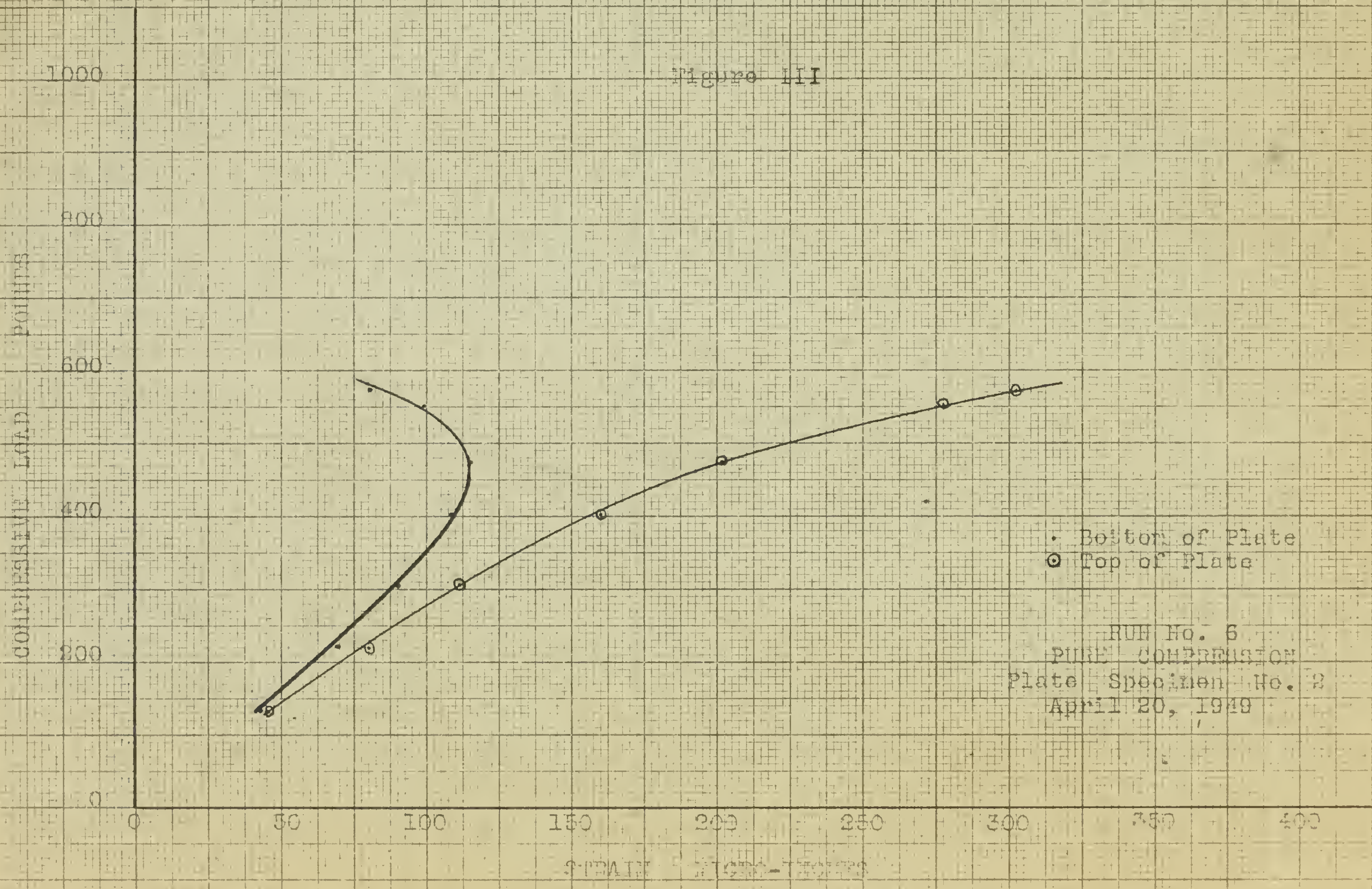
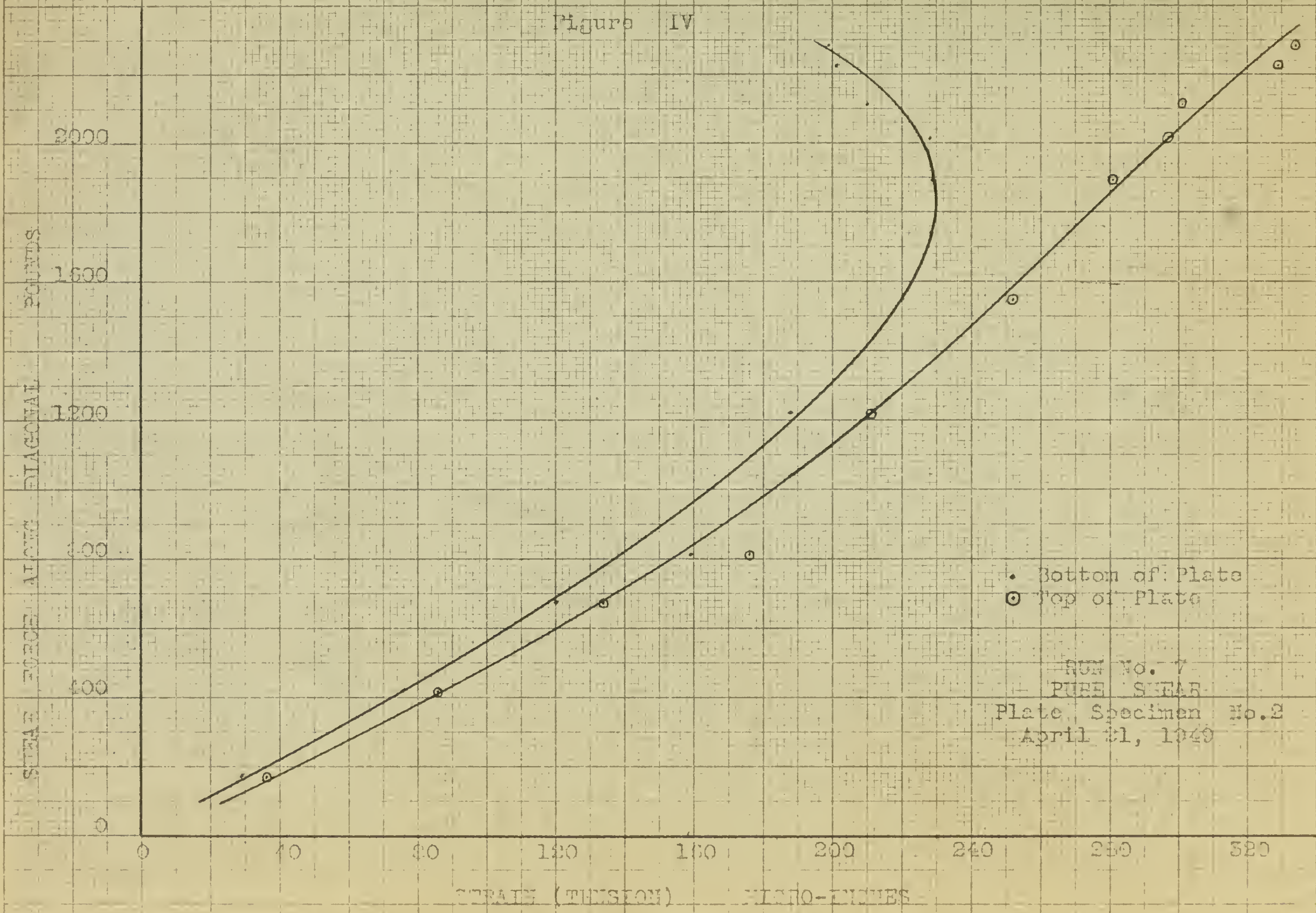

COMPRESSIVE LOAD POUNDS
1000
800
600
400
200
0
0
50
100
150
200
250
300
350
400
· Bottom of Plate
⊙ Top of Plate
RUN No. 6
PURE COMPRESSION
Plate Specimen No. 2
April 20, 1949

Figure III



Bottom of Plate
Top of Plate
RUN No. 7
PURE SHEAR
Plate Specimen No.2
April 21, 1949
SHEAR FORCE ALONG DIAGONAL POUNDS
STRAIN (TENSION) MICRO-INCHES
0
400
800
1200
1600
2000
40
80
120
160
200
240
280
320

Figure IV

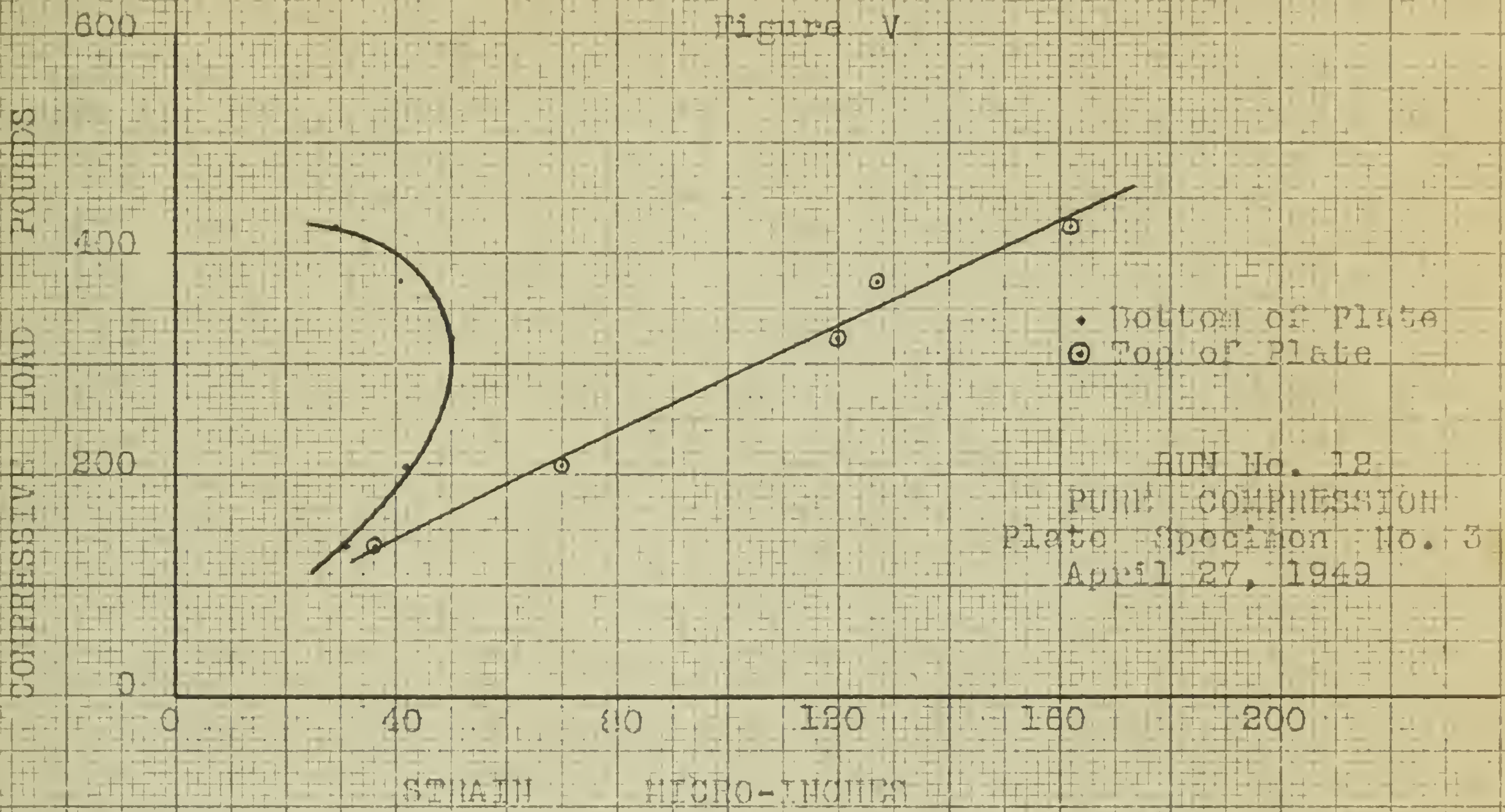


Figure V
COMPRESSIVE LOAD POUNDS
600
400
200
0
0
40
80
120
160
200
STRAIN MICRO-INCHES
• Bottom of Plate
⊙ Top of Plate
RUN No. 12
PURE COMPRESSION
Plate Specimen No. 3
April 27, 1949

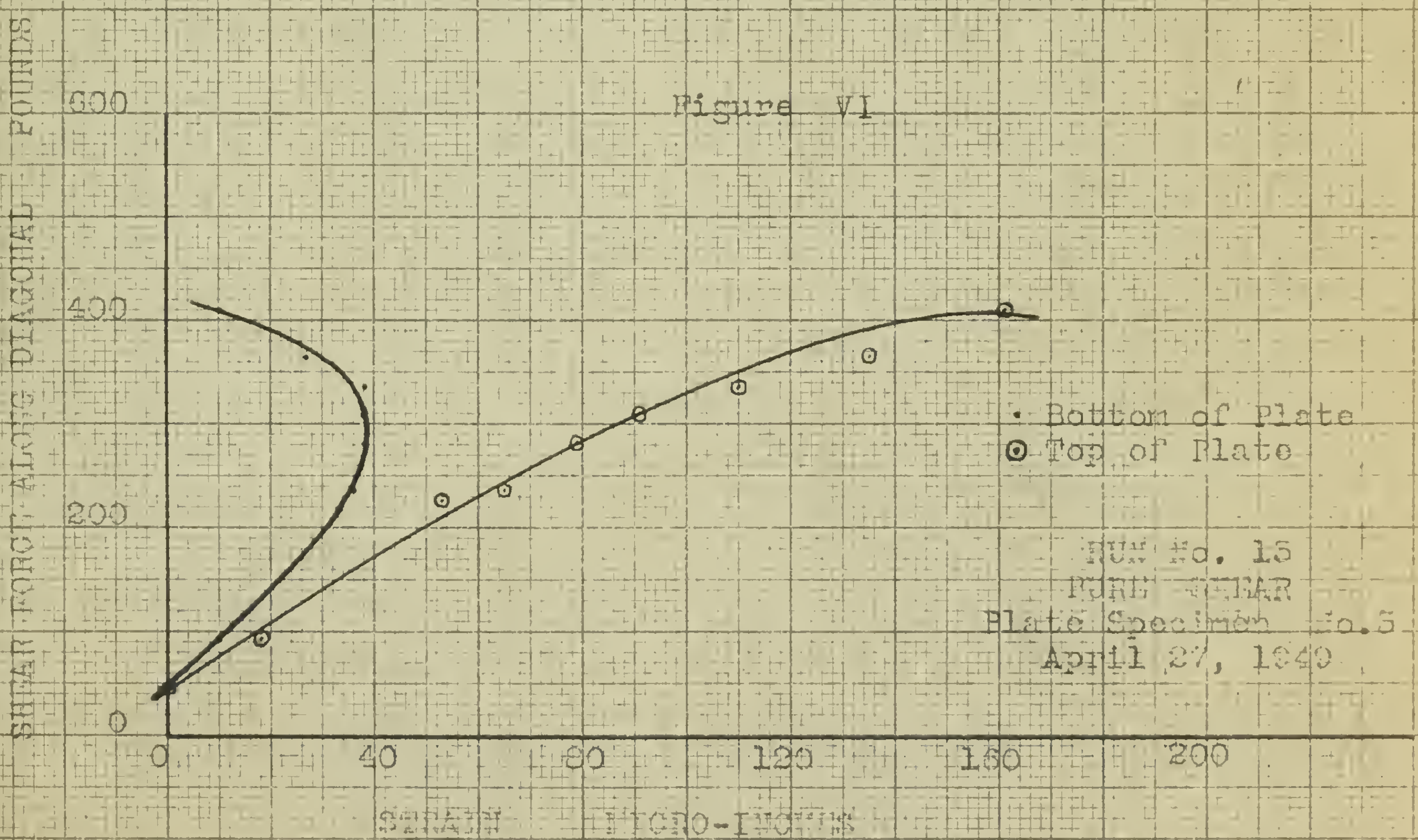


Figure VI
SHEAR FORCE ALONG DIAGONAL POUNDS
600
400
200
0
0
40
80
120
160
200
STRAIN MICRO-INCHES
• Bottom of Plate
⊙ Top of Plate
RUN No. 13
PURE SHEAR
Plate Specimen No.5
April 27, 1949

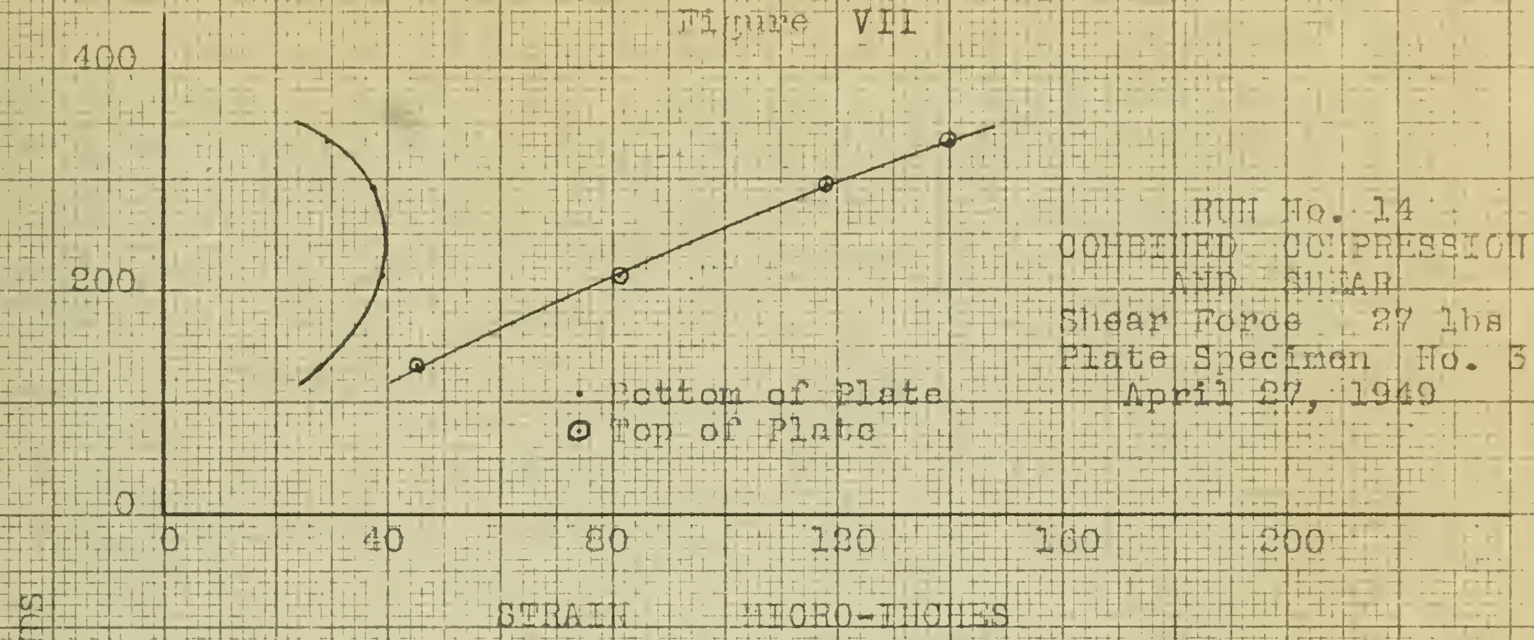
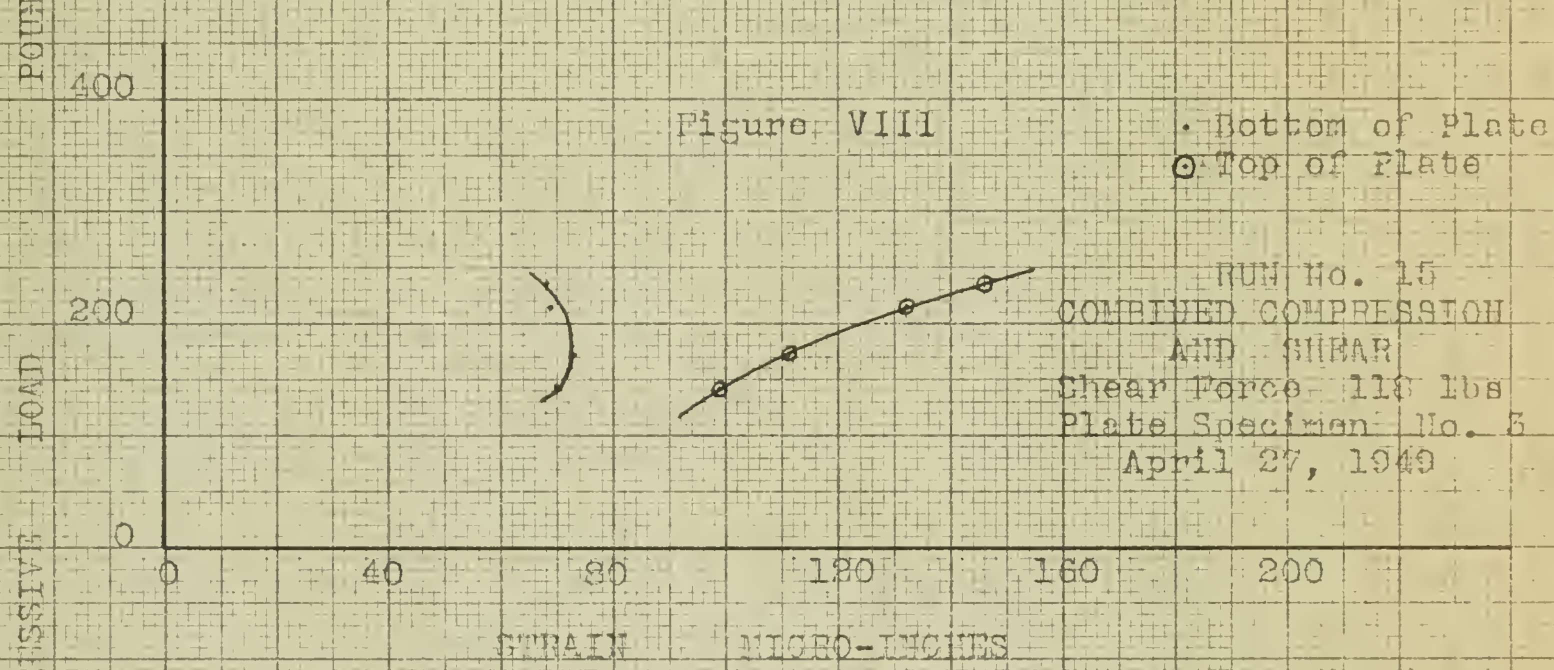


Figure VII



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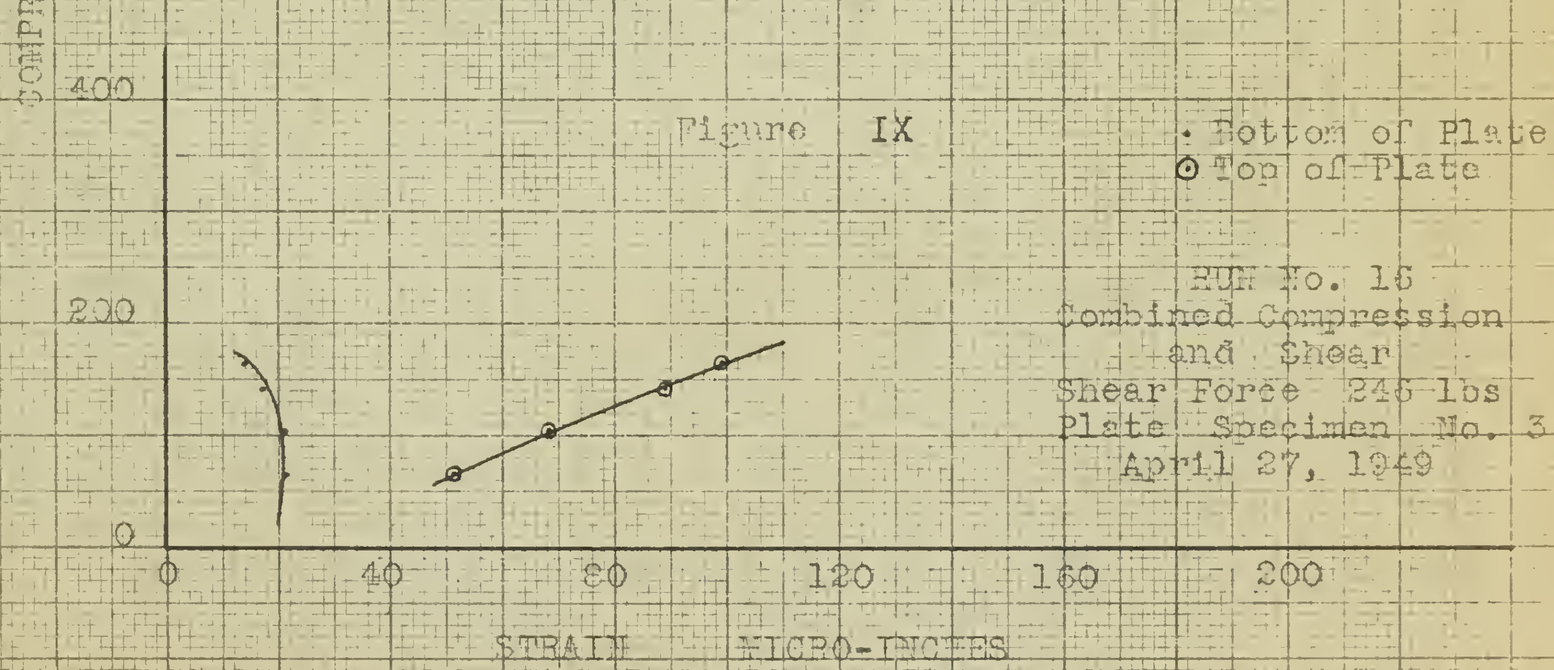


Figure IX

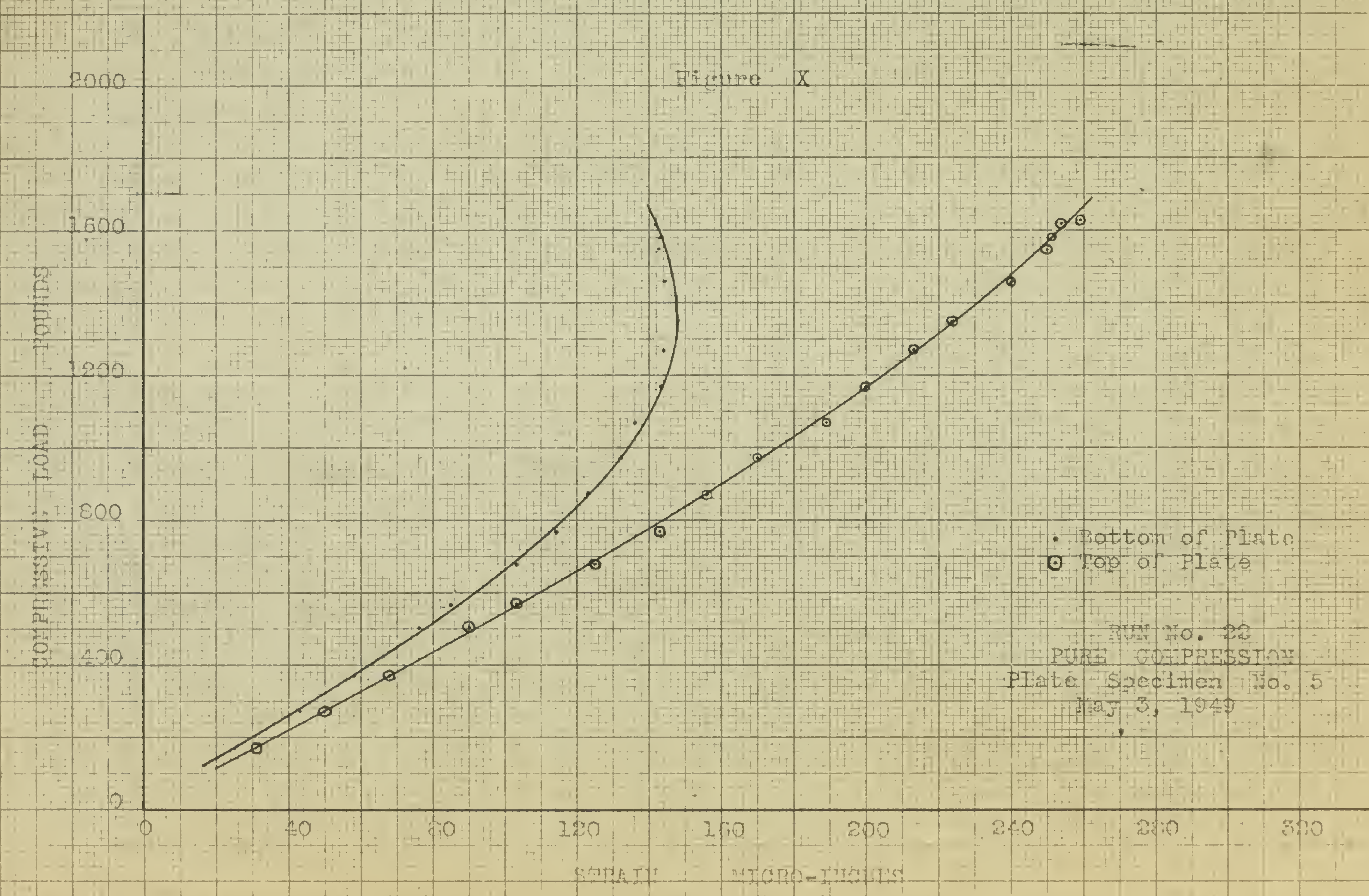


Figure X
COMPRESSIVE LOAD POUNDS
STRAIN MICRO-INCHES
0
400
800
1200
1600
2000
40
80
120
160
200
240
280
320
• Bottom of Plate
⊙ Top of Plate
RUN No. 22
PURE COMPRESSION
Plate Specimen No. 5
May 3, 1949

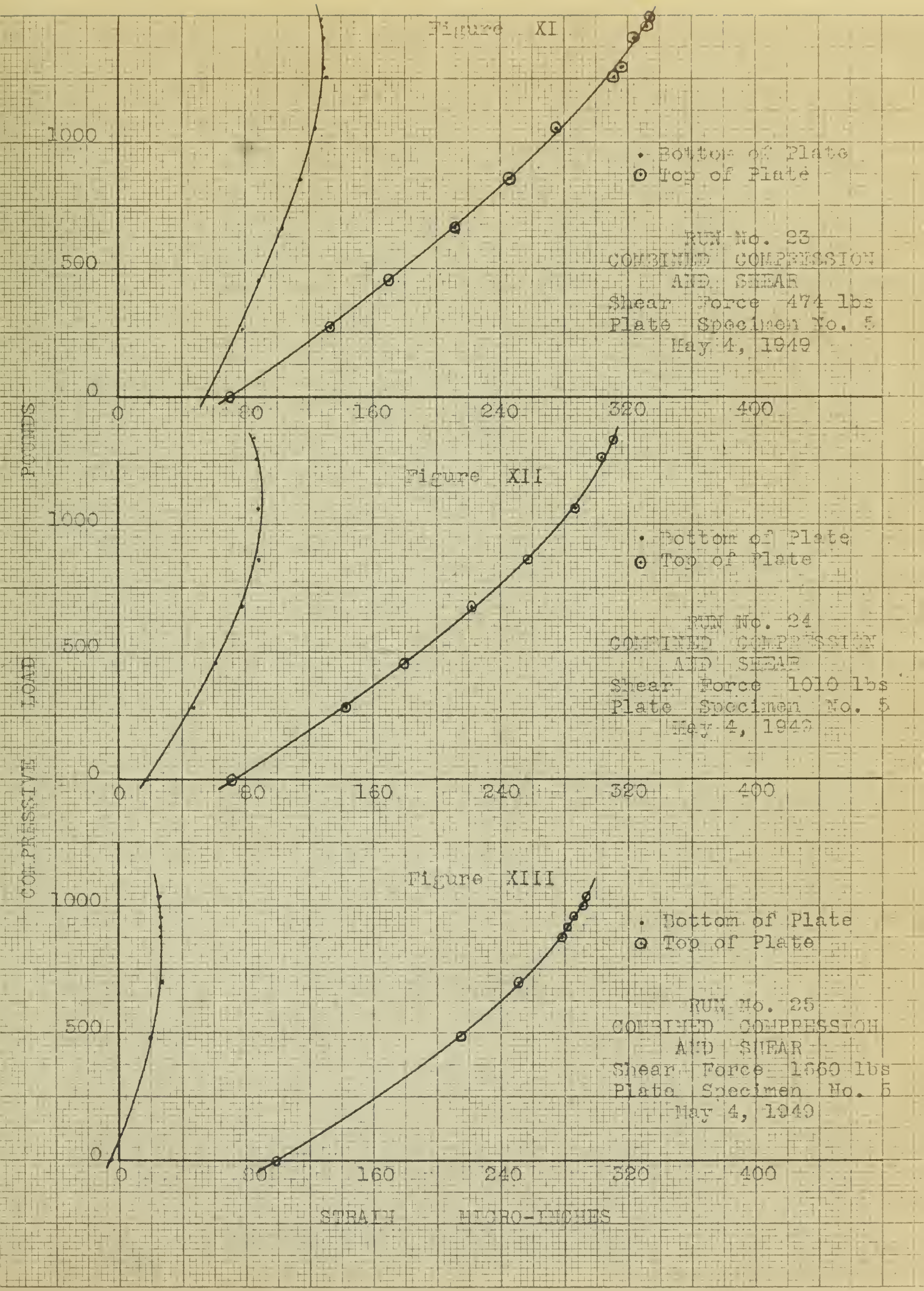


Figure XI
1000
500
0
0
80
160
240
320
400
• Bottom of Plate
⊙ Top of Plate
RUN No. 23
COMBINED COMPRESSION
AND SHEAR
Shear Force 474 lbs
Plate Specimen No. 5
May 4, 1949
Figure XII
• Bottom of Plate
⊙ Top of Plate
RUN No. 24
COMBINED COMPRESSION
AND SHEAR
Shear Force 1010 lbs
Plate Specimen No. 5
May 4, 1949
Figure XIII
• Bottom of Plate
⊙ Top of Plate
RUN No. 25
COMBINED COMPRESSION
AND SHEAR
Shear Force 1660 lbs
Plate Specimen No. 5
May 4, 1949
COMPRESSIVE LOAD POUNDS
STRAIN MICRO-INCHES

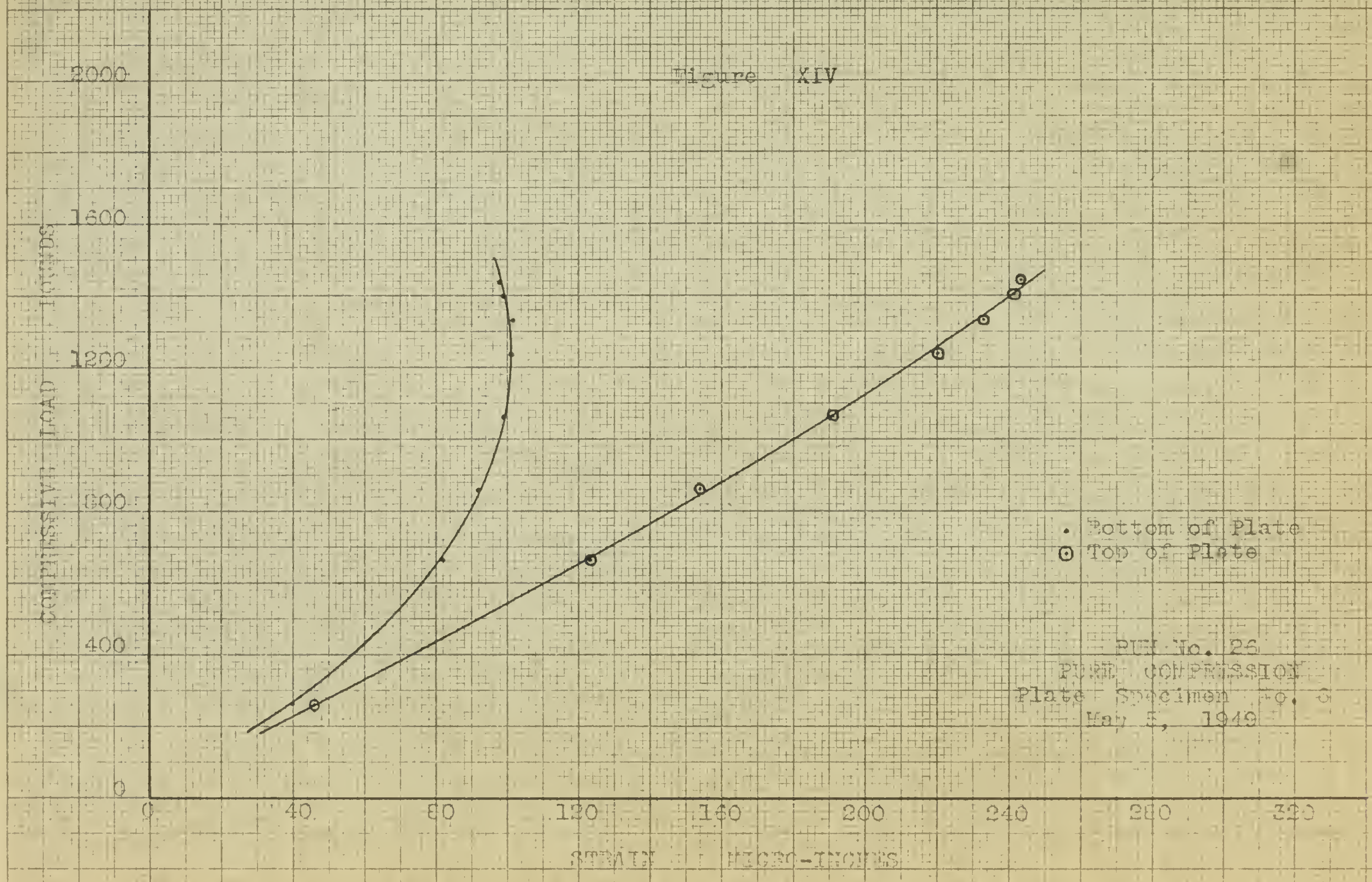


Figure XIV
COMPRESSIVE LOAD POUNDS
2000
1600
1200
800
400
0
0
40
80
120
160
200
240
280
320
STRAIN MICRO-INCHES
· Bottom of Plate
⊙ Top of Plate
RUN No. 26
PURE COMPRESSION
Plate Specimen No. 6
May 5, 1949

Figure XV

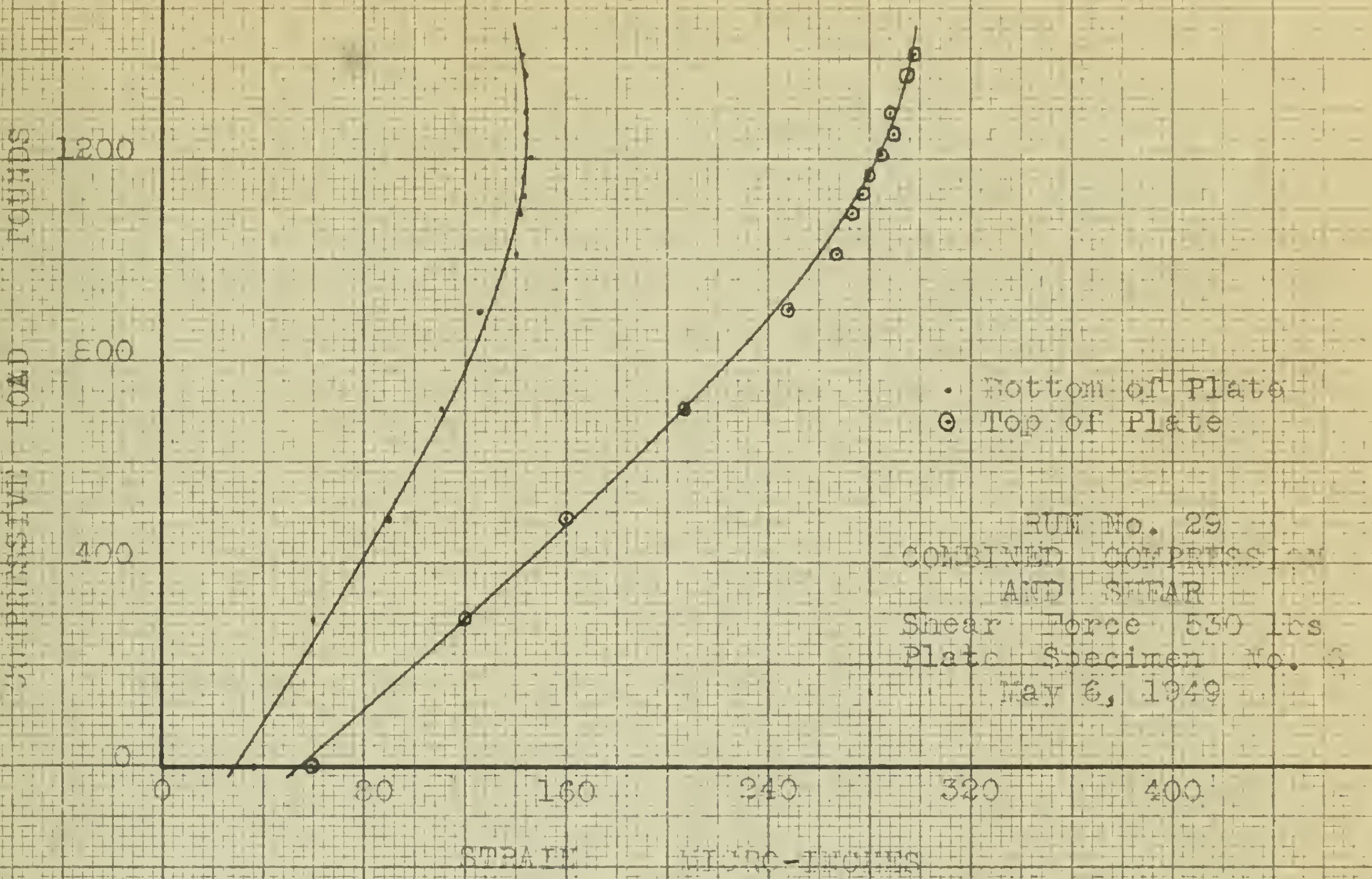
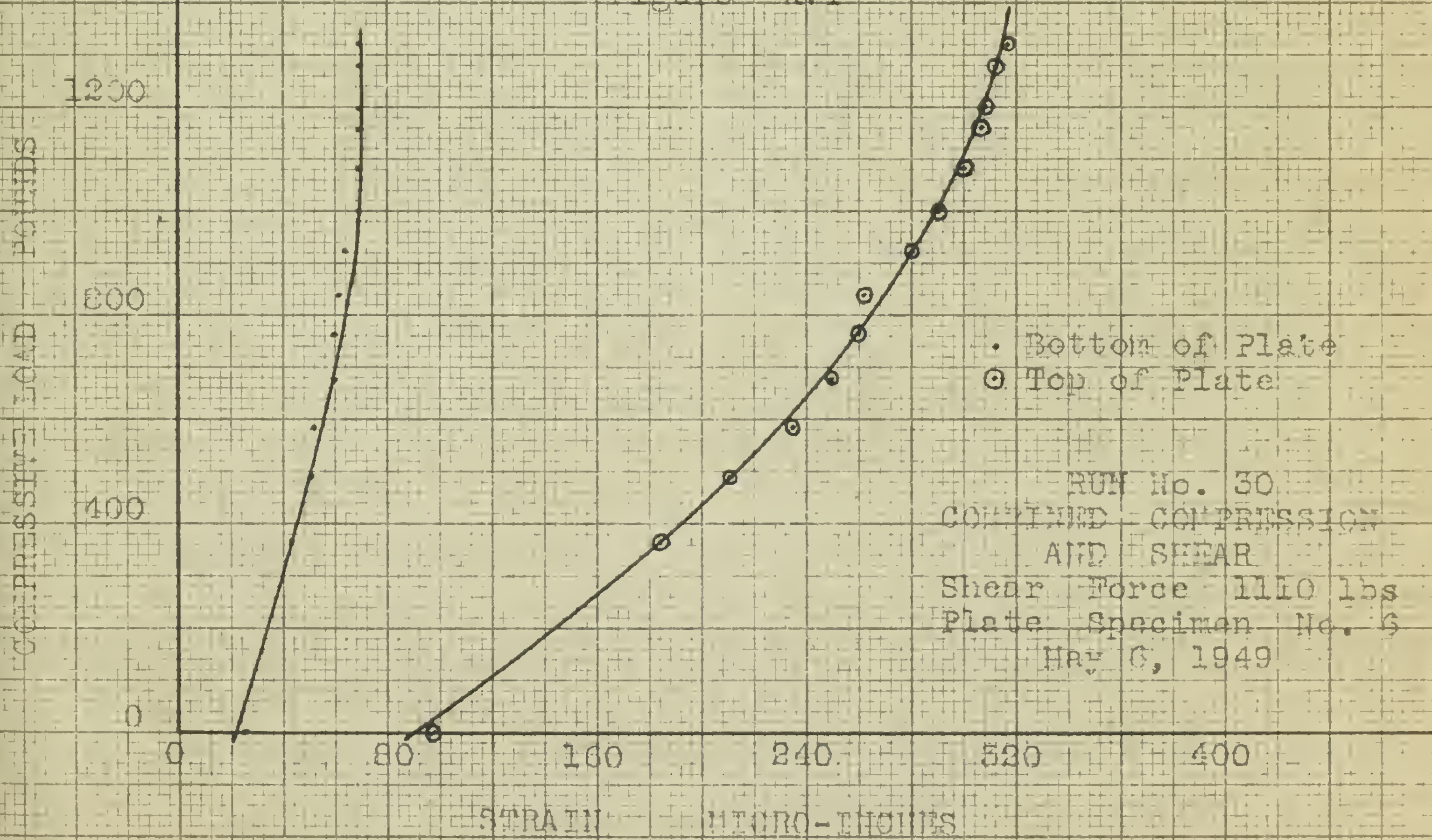


Figure XVI



DISCUSSION OF RESULTS

The major portion of the period available for conducting this investigation was spent in procurement of material, fabrication of the smaller components, and assembly of the testing apparatus. The schedule of testing originally planned was necesserily reduced considerably so that actually only seven specimens were mounted and tested.

An inspection of the results of the several tests conducted in the course of the investigation reveals the difficulty encountered in obtaining consistent values and reproducing similar conditions of installation of the specimen. The principal conclusions which can be drawn from the test data obtained are that the apparatus as designed and assembled is capable of applying load to the specimen and that the buckled condition of the specimen can be attained.

Only two SR-4 strain gauges were mounted on the specimens. These were located at the centers of the panels, arranged longitudinally, one on the upper side and the second directly beneath it on the lower side. By means of these gauges, buckling of the plate was detected. When the buckling condition was reached, these gauges no longer indicated a parallel trend of increasing strain. The formation of the buckling wave in the panel then caused tension on one side and increased compression on the opposite side of the panel. The necessity for accurate positioning of these gauges is obvious. In a few instances, formation of the buckling

wave was observed visually shortly before the gauge indications were recorded. It was not possible to maintain a constant visual observation of the panel to detect this phenomenon nor was it possible to determine the magnitude of the force at that particular instant, therefore only the strain gauge indications were relied upon as the criteria for the attainment of the buckled condition.

The general trend of the plots included in this report indicates that the performance of all specimens conformed to the expected indications of variation of strain with increasing load. The exact causes for the inconsistent values of buckling loads are not known. Several factors are considered to have contributed to the erratic results.

The most important feature in the assembly of the apparatus and the specimen is the large amount of accurate machining of parts that is required. As the plate specimen is mounted, any misalignment occurring, which results in a necessarily forced fit, probably causes the creation of a local, indeterminate condition of stress which may or may not affect the performance of the plate under test. It is essential that great precision and care be exercised in the fabrication of the lateral supports and that all plates used for purposes of comparison be prepared simultaneously and be identical.

were was observed visually shortly before the gauge indications were recorded. It was not possible to maintain a constant visual observation of the panel to detect this phenomenon nor was it possible to determine the magnitude of the force at that particular instant; therefore only the strain gauge indications were relied upon as the criteria for the attainment of the buckling condition.

The general trend of the plots included in this report indicates that the performance of all specimens conformed to the expected indications of variation of ripple with increasing load. The exact causes for the inconsistent values of buckling loads are not known. Several factors are considered to have contributed to the erratic results.

The most important feature in the assembly of the apparatus and the specimens is the large amount of accurate machining of parts that is required. As the plate specimen is mounted, the misalignment correction, which results in a geometrically forced fit, probably causes the creation of a local, indeterminate condition of stress which may or may not affect the performance of the plate under test. It is essential that great precision and care be exercised in the fabrication of the lateral supports and that all plates used for purposes of comparison be prepared simultaneously and be identical.

In the application of the compressive load to the plate it was frequently observed visually that bending of the plate and the lateral supports occurred. In this condition, the applied loads are no longer truly in the plane of the plate and an uncontrolled condition exists. The aligning strips at the ends of the lateral supports were installed for the purpose of minimizing the bending effect. It would seem advisable to extend these strips a greater length on the compression pieces to further reduce this bending effect. The aligning strips must be free to slide on the compression pieces when shearing forces are applied to the plate, therefore, it may be advisable to apply a lubricant to the adjacent surfaces.

In the performance of the several tests conducted it was observed that more consistent results were obtained after a number of tests had been made on a particular specimen. This would indicate that it may be advantageous to slowly apply the load to the specimen several times before beginning to record data. It was discovered that after applying a shearing force of sufficient magnitude to cause buckling, the plate was distorted to such an extent that further tests were valueless.

In the course of the investigation, two arrangements for the application of shear were used. The first design depended upon the simultaneous, even distribution of shearing force to the plate through twenty $\frac{1}{4}$ inch bolts,

evenly spaced on each side of the plate. This arrangement was not tested completely because the vertical travel of the jack for applying shear forces, did not permit the application of the desired magnitude of shearing force and it was apparent that, due to slight inaccuracies in the fabrication of the components, all twenty of the bolts on a side would not come into action simultaneously. The second design utilized four $\frac{1}{2}$ inch pins on each side of the plate. These were equally spaced and were connected by linkages which theoretically should have caused equal distribution of the shearing forces applied to the plate. Runs Nos. 14, 15, and 16 which were conducted on Specimen No. 3 gave results which conformed to the trend of the theoretical solution of Warren (6), i.e. the stability of the panel in compression is reduced by shear. These were the only combined runs which indicated that the apparatus was functioning properly. An investigation of the stress distribution in this loading device by means of SR-4 gauges placed on each of the twenty-four links would indicate the effectiveness and accuracy of the system and may lead to a more satisfactory method for equal distribution of load.

The values of critical, or buckling, stress are directly proportional to the square of the thickness to width ratio of the specimen. Micrometer measurements

evenly spaced on each side of the plate. This arrangement was not tested completely because the vertical travel of the [illegible] for applying these forces, did not permit the application of the desired magnitude of shearing force and it was apparent that, due to slight inaccuracies in the fabrication of the components, all twelve of the bolts on a side would not come into action simultaneously. The second fixture utilized four 1 inch bolts on each side of the plate. These were equally spaced and were connected by linkages which theoretically should have caused equal distribution of the shearing forces applied to the plate. Test Nos. 16, 17, and 18 which were conducted on specimen No. 4 gave results which conformed to the trend of the theoretical solution of Warren (6), i.e. the stability of the panel in compression is reduced by shear. These were the only completed runs which indicated that the apparatus was functioning properly. An investigation of the stress distribution in this loading device by means of SR-4 gauges placed on each of the twenty-four links would indicate the effectiveness and accuracy of the system and may lead to a more satisfactory method for equal distribution of load.

The values of critical, or buckling, stresses are directly proportional to the square of the thickness to width ratio of the specimen. Accurate measurements

were made of plate thicknesses and the values recorded. It has been assumed that the effective width of the specimens equalled the unsupported width between lateral supports, namely, six inches. Due to the unavoidable differences in tightness of bolts, the effective width might actually have been closer to seven inches, which is the distance between the rows of bolts. If the plates were similar in all other respects, the variation in effective width would have been negligible.

The turnbuckle device for tightening the shear cable and measuring the shear force applied to the specimen functioned in a very satisfactory manner. Strain readings taken on the SR-4 gauges attached to the turnbuckle indicated that it was subjected to bending. Steps should be taken to insure that the optimum alignment is attained for this device, otherwise twisting of the lever plate and linkages will occur which may adversely affect the specimen.

If future investigations are to be conducted in this field, it may be advisable to utilize a material having a low modulus of elasticity for the components in contact with the specimen. This will lessen the tendency for the lateral supports to act as stiffeners and may lead to more accurate and reliable results.

CONCLUSIONS

1. The apparatus as designed and assembled is capable of applying compressive and shearing forces to the specimens.

2. Although in only one complete series of runs it was found that shear reduced the stability of plating in compression, it is felt that this result may be consistently reproduced if the apparatus is more carefully assembled and aligned.

3. More consistent results are obtained if several runs are made before data is recorded, provided that the specimen is not subjected to the critical shearing force.

4. Bending occurring during compression deflects the plate so that it is no longer subjected to loading only in its own plane, thereby introducing a third and indeterminate type of loading.

5. Buckling may occur shortly before the SR-4 gauges indicate its effect, therefore more gauges on the specimen may be necessary to detect the formation of the initial buckling wave.

RECOMMENDATIONS

1. An analysis of the shear distribution linkage system by means of SR-4 gauges should be made to determine the effectiveness of the system and to determine possible improvements.

2. Components of the shear loading device in contact with the plate should be made of a material of low modulus of elasticity to minimize the stiffening effect of the lateral supports.

3. Aligning strips should be extended to reduce the possibility of bending the specimen under a compressive load.

4. The turnbuckle device should be adjusted so that it is free from bending effects and will not cause rotation of the lever plate to which it is attached. Careful adjustment of the shear cable may assist in reducing bending of the turnbuckle. A more permanent location for the strain gauges in the shear system may be desirable inasmuch as it has been frequently found necessary to disconnect the leads from the gauges when rotating the turnbuckle.

APPENDIX

APPENDIX A

DETAILS OF PROCEDURE

Description of Apparatus

Specimen

The specimens were Aluminum plate AL-52-½H conforming with Navy Specification 47-A-11. The characteristics of this material are; modulus of elasticity 10,300,000 psi, tensile strength 34,000 psi, yield strength 26,000 psi, shear strength 20,000 psi, endurance limit 18,000 psi, and elongation in 2 inches 12 per cent. The plates were 22.5 inches long and 8 inches wide, the clear dimensions between end compression pieces and between lateral support members thus becoming 21 inches by 6 inches. The latter dimensions were used in all computations for critical buckling loads for a length-width ratio of 3.5 to 1.

The ends of the plate were drilled with ¼ inch diameter holes to line-up with those drilled in the end compression attachments. They were spaced 3/8 inches from the end of the plate and at 1 inch intervals except at the sides where the holes were drilled at 5/8 inches from the sides so as to be in line with the row of bolts along the lateral support members.

The four holes on either side of the plate which accommodate the four shear distribution pins were ½ inch in diameter and spaced 2 5/8 inches from either end with 5¼ inch spacing between the holes, and ½ inch from the edge of the plate. The holes for the screws holding the lateral supports

in place were approximately 11/64 inches in diameter, spaced at about 1 inch intervals between the ½ inch holes along the edge, and 5/8 inches from the edge of the plate.

Lateral Supports

The lateral supports were four in number two on either side, on top and bottom of the plate. They were 5/16 inch by 1 inch steel strips, 20 3/4 inches long. When bolted to the plate specimen there was a gap between them and the end compression attachments of approximately 1/8 inch. Holes of 11/64 inch diameter coincided with those drilled in the plate specimen for the 8-32 screws which bolted the lateral supports to the plate. Holes of 5/8 inch diameter were drilled in the lateral supports, concentric with the four ½ inch holes on each side of the plate. Thus the shear distribution pins did not transmit their force into the lateral supports, but instead, directly into the plate.

Shear Distribution Pins and Linkage Bars.

The four ½ inch diameter pins are shown in sketch in Appendix B as I, II, III, and IV. Pin I is acted upon by a force F/2 which is applied at 1 1/4 inches on either side of the plate specimen. This force F/2 is transmitted from the lever plate through a steel bar 5/16 inch by 1 inch in cross section. Bar A of cross section 3/16 inch

by 1 inch acts at a point 1 inch on either sids of the plate. The position of Bar A was calculated to transmit a force F/4 into the plate at the center of pin I. Bars B and C were similarly located, so that one fourth of the applied shear load is transmitted into the plate at the center of pins II, III, and IV. Bars A, B, and C each have ½ inch diameter holes drilled on 5½ inch centers. Bar A pulls on pin II at 1 inch from the pin center. Bar B of cross section ½ inch by 7/8 inch pulls on pin II at 3/4 inch from the pin center, and also on pin III at the same location. Bar C of cross section ½ inch by 1 inch pulls on pin IV at ½ inch from the pin center. The bars A, B, and C are held at their correct position by insertion of spacers concentric with the pins. The sample calculations for this distribution system are given in Appendix B.

Aligning Strips

Short sections of 1/8 inch by 1 inch steel strips approximately 3 inches long were bolted at each of the four corners of the plate, one piece on both top and bottom. Two holes were drilled to coincide with the 11/64 inch holes drilled in the lateral supports, and a third hole was concentric with the ½ inch hole in the compression attachment, which was 5/8 inch from its edge. This latter hole was enlarged considerably to permit relative

movement of the lateral supports, and the compression attachments. The purpose of these pieces of metal was to prevent unintentional bending of the plate specimen between the end compression attachments and lateral supports, and yet permit the compressive force to be exerted directly on the plate without being introduced into the lateral support members.

Compression Attachments

The two identical compression attachments consisted of a section of 1¼ inch standard steel pipe 8 inches long, to which was welded a piece of ½ inch steel plate 8 inches long by 3¼ inches wide, so that the steel plate extended radially outward from the center of the steel pipe. The outer 8 inch by ½ inch edge of this plate had a slot milled 3/4 inch deep by 1/8 inch wide centrally located along this edge. The ¼ inch holes drilled at 3/8 inches from the edge and equally spaced at 1 inch intervals corresponded to those drilled in the end of the plate specimen. A 3/8 inch hole was drilled at 1 3/4 inches from the outer edge and 2 inches from one side to provide the connection for the linkage bars to the lever plate.

End Frames

The two end frames were identical in construction. The material consisted of ¼ inch mild steel plate, joined to sections of 1 inch extra strong steel pipe and 1¼ inch

standard steel pipe. The $1\frac{1}{4}$ inch pipe with inner diameter 1.380 inches permits the 1 inch pipe with outer diameter 1.315 inches to fit loosely within it and forms the pivoting axes of the compressing device. The distance center to center from the lower pipe section to the upper pipe section was 9 inches. The distance from center of the lower pipe section to the vertical mounted reinforcing plate section was 3 feet. It was beneath this reinforced section at which the hydraulic jack force was applied at one end, and beneath which a line of contact with the balance scale was established on the other end. These dimensions gave a 4 to 1 ratio between applied force and that actually exerted on the plate specimen.

Balance Scale and Hydraulic Jack

The balance scale capacity was 1000 pounds. It was this value which established the maximum design conditions in this investigation. The hydraulic jack, which was purchased commercially, had a capacity of 3 tons.

Lever Plates

The two identical lever plates were constructed from $\frac{1}{4}$ inch steel plate, cut to provide clearance for operation of the apparatus. Three $\frac{1}{4}$ inch holes were positioned so that their centers formed a right triangle with the longer leg $17\frac{1}{2}$ inches and the shorter leg 5 inches, main-

taining the 3.5 to 1 ratio of the plate specimen.

Turnbuckle and Strain Gauge Device

This device was designed by the authors and was made by the M.I.T. Civil Engineering Structural Laboratory personnel. Two flat areas were milled on diametrically opposite sides of a piece of 1 inch diameter bar stock. Cross sectional area of bar between milled flats was 0.6075 sq. inches. Width of milled section was 0.75 inches, and the length approximately 2½ inches. The length of the threaded travel was 4 inches.

Wire Rope

The shearing force was applied through approximately 14 feet of 6 x 19 ½ inch wire rope which has the following characteristics; metallic area 0.098 sq.in., modulus of elasticity 12,000,000 lbs./sq. in., and breaking strength 9.35 tons. This wire rope was connected to the lever plate directly on one end by a standard 3/4 inch shackle, and on the other end to the turnbuckle by the same size shackle with modifications to suit the design.

I-Beam and Sheaves

The I-beam was a standard 8 x 4 x 12# beam which had a section modulus of 1.44 inches cubed, for the position in which mounted. At each end 10 inches of the web was removed to permit insertion of sheaves. These were standard 12 inch sheaves, bronze bushed, with 1 inch diameter shafts.

The shafts were supported by the two flanges of the I-beam, through which 1 inch diameter holes were drilled. The holes for these shafts were 4 feet 9 inches from the center of the beam. The I-beam was supported by 2 x 4 pine members, bolted at each end so that the center of the sheave shafts were approximately 5 feet above the floor level.

Shearing Force Jack

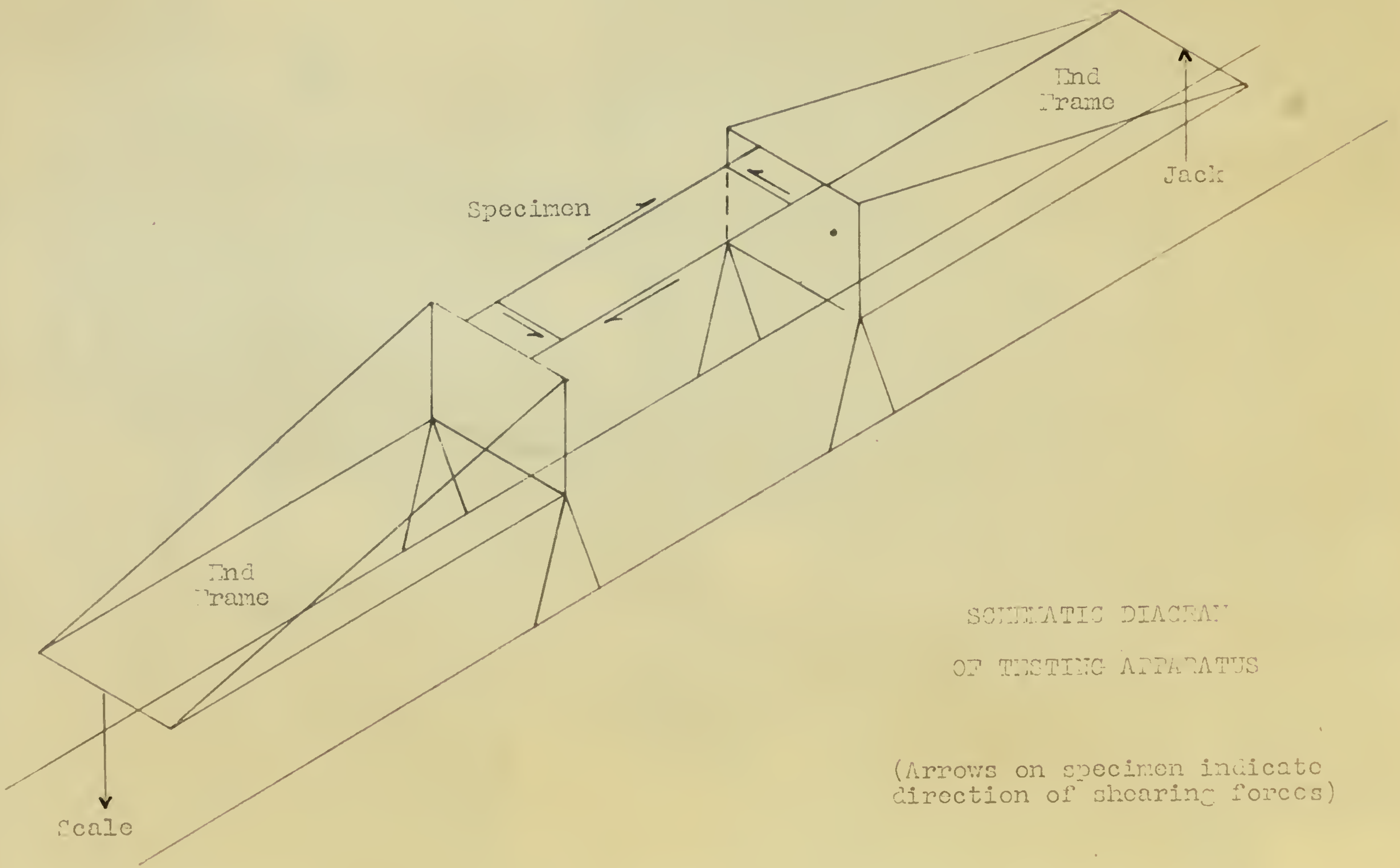
The vertical jack screw at the center of the beam held the center of the wire rope at approximately 10½ inches above the center of the web of the beam. An additional travel of 4½ inches was available on the threaded portion of the screw to raise the wire height to approximately 15 inches above the center of the web. The vertical movement of this screw was designed to transmit 10,000 lbs into the wire rope, however this force was subject to variation, dependent on the initial force in the cable when the turnbuckle was tightened. In the tests performed, forces as great as 4000 lbs. were measured.

Strain Gauges and Strain Indicator

The SR-4 strain gauges were Bonded Resistance Wire Gauges manufactured by the Baldwin Southwark Division, Baldwin Locomotive Works. The specific gauge used was an A-11, 119.2 ohm, with gauge factor 2.04. The strain

readings were obtained by the use of an SR-4 Strain Gauge Indicator, also manufactured by Baldwin. The strain gauges were mounted on both sides of the plate specimen, and at the center of the plate, with their axis parallel to the longer dimension of the plate.

Figure XVII

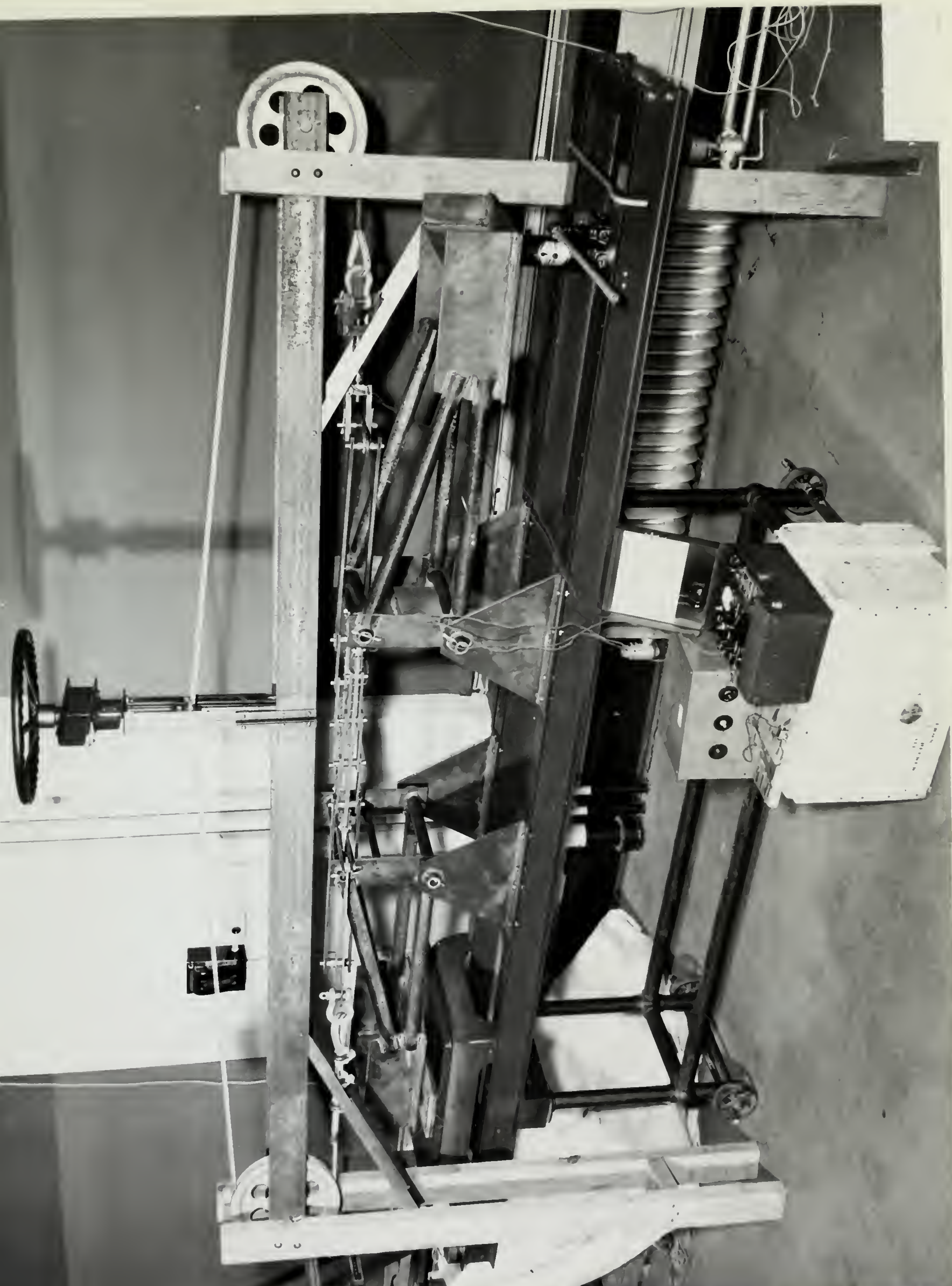


SCHEMATIC DIAGRAM

OF TESTING APPARATUS

(Arrows on specimen indicate direction of shearing forces)

Figure XVIII

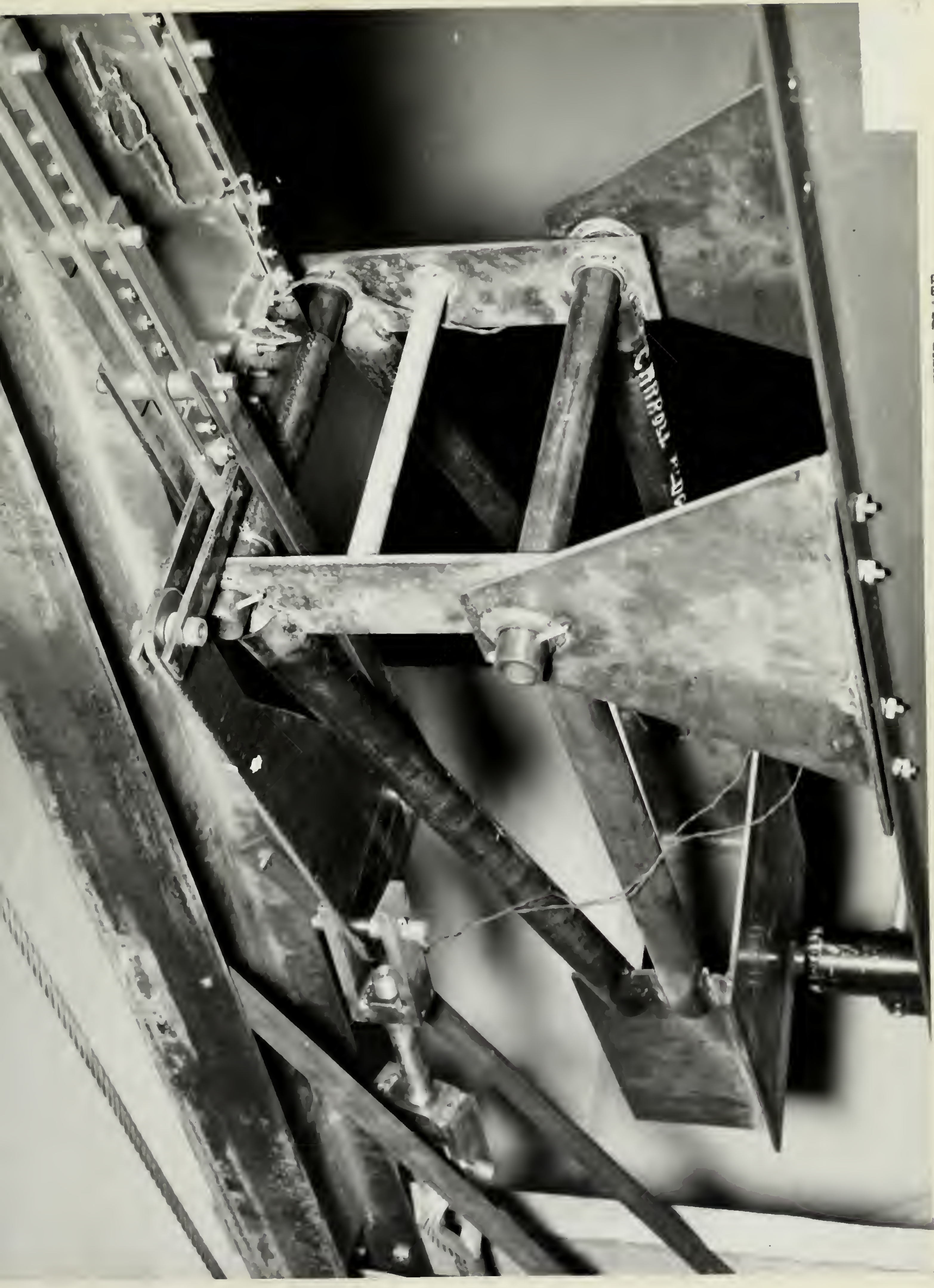


TESTING APPARATUS

Figure XIX

PLATE SPECIMEN AND SHEAR L... [illegible]

Figure XX



TURNBUCKLE AND STRAIN GAUGE DEVICE CONNECTED TO LEVER PLATE

APPENDIX B

SAMPLE CALCULATIONS

Calculations for Theoretical Critical Values of Stress

Formulas for Critical Stress:

Compressive Stress: $$\sigma_{CR} = K \frac{\pi^2 E}{12(1-\nu^2)} \times \frac{t^2}{b^2}$$

Shear Stress: $$\tau_{CR} = K_s \frac{\pi^2 E}{12(1-\nu^2)} \times \frac{t^2}{b^2}$$

For plate freely supported on all four sides and with length-to-width ratio of 3.5 –

$$K = 4.00$$

$$K_s = 5.40$$

Formulas and constants from Timoshenko (3).

In the above formulas –

E is the modulus of elasticity of the material and equals 10,300,000 pounds per square inch.

ν is Poisson's ratio and equals 0.33.

t is plate thickness.

b is plate width, assumed to be 6 inches.

Specimen	t, inches	σ_{CR}, kips/in. sq.	τ_{CR}, kips/in. sq.	Max. Comp. Force, kips	Max. Shear Force, kips
No.1	0.039	1.609	2.170	0.376	1.845
No.2	0.033	1.150	1.552	0.228	1.118
No.3	0.033	1.150	1.552	0.225	1.113
No.4	0.0395	1.650	2.225	0.391	1.[illegible]0
No.5	0.064	4.330	5.840	1.662	8.150
No.6	0.065	4.460	6.030	1.742	8.545
No.7	0.030	0.952	1.[illegible]87	0.171	0.840

The maximum compressive force is obtained by multiplying the critical compressive stress by the cross-sectional area of the specimen.

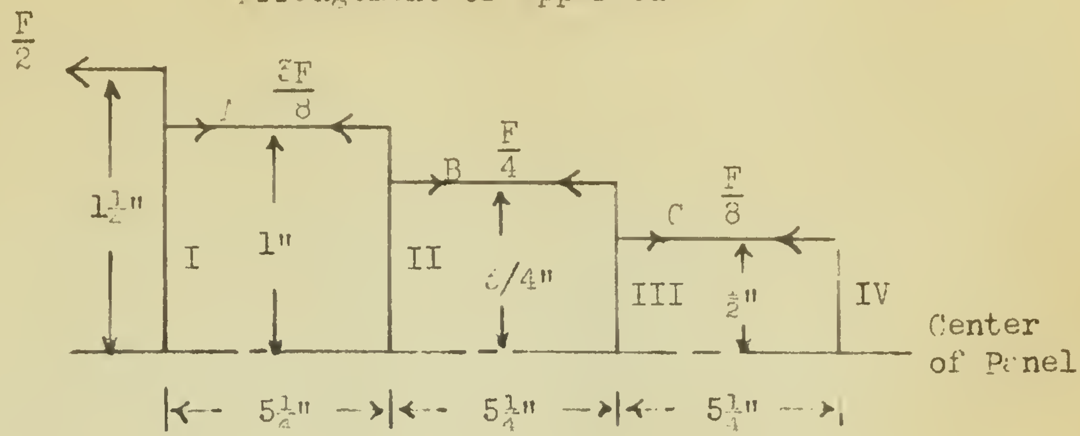
The maximum shear force is obtained by multiplying the critical shear stress by the product of the thickness, t, and the length. It is further corrected by resolving it to the component along the diagonal of the specimen, in which direction the measurements of shear force were obtained.

APPENDIX B

SAMPLE CALCULATION

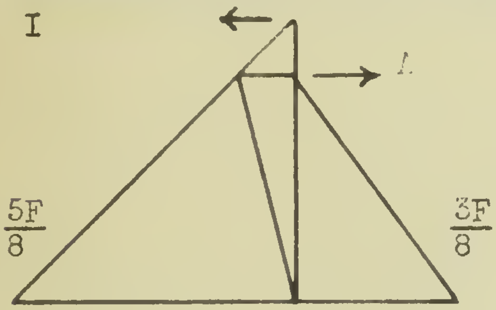
Apparatus for Uniform Distribution of Shearing Force on Side of Panel

Arrangement of Apparatus



Determination of Deflections of Pins

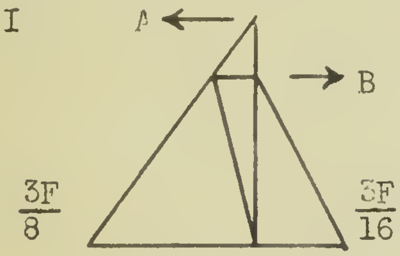
I



$$\Delta_{IA} = \frac{1}{EI}\left(\frac{5F}{8} \times \frac{1}{2} \times \frac{2}{3} + \frac{F}{8} \times \frac{1}{2} \times \frac{1}{3} - \frac{3F}{8} \times \frac{1}{2} \times \frac{2}{3}\right)$$

$$= 0.104\,\frac{F}{EI}$$

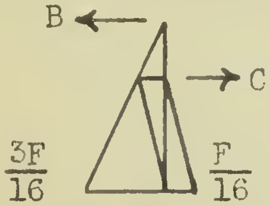
II



$$\Delta_{IIA} = 0.072\,\frac{F}{EI}$$

$$\Delta_{IIB} = 0.044\,\frac{F}{EI}$$

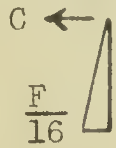
III



$$\Delta_{IIIB} = 0.026\,\frac{F}{EI}$$

$$\Delta_{IIIC} = 0.013\,\frac{F}{EI}$$

IV



$$\Delta_{IVC} = 0.0052\,\frac{F}{EI}$$

APPENDIX B

SAMPLE CALCULATIONS

Determination of Elongation of Bars

$$A:\ \Delta = \frac{Pl}{AE} = \frac{\frac{3F}{8} \times 5\frac{1}{4}}{AE} = 1.97\ \frac{F}{AE}$$

$$B:\ \Delta = \frac{Pl}{AE} = \frac{\frac{F}{4} \times 5\frac{1}{4}}{AE} = 1.31\ \frac{F}{AE}$$

$$C:\ \Delta = \frac{Pl}{AE} = \frac{\frac{F}{8} \times 5\frac{1}{4}}{AE} = 0.66\ \frac{F}{AE}$$

Pin Diameters Assumed to be ½"

$$I = \frac{\pi d^4}{64} = 0.00307\ ''^4$$

Required Elongations of Bars

$$\Delta_{I_A} - \Delta_{II_A} = 10.5\ \frac{F}{E} = \Delta_A$$

$$\Delta_{II_B} - \Delta_{III_B} = 5.8\ \frac{F}{E} = \Delta_B$$

$$\Delta_{III_C} - \Delta_{IV_C} = [illegible]\ \frac{F}{E} = \Delta_C$$

Required Cross-Sectional Areas of Bars

$$A_A = \frac{1.97}{10.5} = 0.1875\ ''^2$$

$$A_B = \frac{1.31}{5.8} = [illegible]\ ''^2$$

$$A_C = \frac{0.66}{[illegible]} = [illegible]\ ''^2$$

APPENDIX C

ORIGINAL DATA

Specimen: Plate No. 1 Plate thickness: 0.039 inches

Conditions: Lateral supports of ¼ inch by 1 inch cross section. Bolt holes in lateral supports ¼ inch diameter spaced at 1 inch intervals. Size 12-24 bolts used in the ¼ inch holes. Used ¼ inch bolts in end compression attachment holes. Shear force attachments disconnected from the plate specimen. All bolts finger tight.

RUN No. 1 Date: 24 March 1949

Type: Pure Compression

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
72	- 25	- 19
204	- 72	- 54
288	- 110	- 89
352	- 142	- 101
480	- 198	- 102
580	- 246	- 103
676	- 311	- 83
780	- 391	- 43
896	- 423	- 7

RUN No. 2 Date: 24 March 1949

Type: Pure Compression

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
42	- 19	- 32
78	- 49	- 47
120	- 51	- 61
156	- 93	- 86
280	- 111	- 85
325	- 129	- 89
388	- 131	- 102
440	- 150	- 115
476	- 173	- 125
524	- 200	- 124
556	- 228	- 123
596	- 258	- 106
640	- 289	- 96
680	- 318	- 64
712	- 324	- 53
760	- 348	- 37
800	- 376	- 23
832	- 392	- 5

Specimen: Plate No. 1 Plate thickness: 0.039 inches

Conditions: The same as Run No. 1.

RUN No. 3 Date: 31 March 1949

Type: Pure Compression

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
94	- 33	- 28
178	- 59	- 53
256	- 93	- 74
336	- 123	- 97
396	- 104	- 74
480	- 163	- 104
572	- 233	- 100
652	- 284	- 82
712	- 301	- 23
784	- 341	+ 3

Specimen: Plate No. 1 — Plate thickness: 0.039 inches

Conditions: Lateral supports the same as Run No. 1 with the exception that ¼ inch bolts were used in the ½ inch bolt holes of the lateral supports. All other conditions the same as Run No. 1.

RUN No. 4 Date: 5 April 1949

Type: Pure Compression

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
108	- 30	- 30
208	- 70	- 66
300	- 107	- 103
364	- 126	- 121
440	- 152	- 153
520	- 169	- 182
596	- 179	- 211
680	- 147	- 269
736	- 113	- 321
828	- 30	- 374
904	+ 17	- 424

RUN No. 5 Date: 5 April 1949

Type: Pure Compression

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
112	- 22	- 22
216	- 58	- 59
284	- 83	- 87
356	- 108	- 110
444	- 138	- 143
524	- 162	- 181
620	- 162	- 231
656	- 138	- 272
756	- 81	- 352
848	- 62	- 393
928	- 53	- 409

Specimen: Plate No. 2 Plate thickness: 0.033 inches

Conditions: Lateral supports of cross section 3/16 inch by 1 inch, bolt holes 11/64 inch diameter, lateral supports held to plate specimen by 8-32 size screws, finger tight. Shear force attachments connected to plate specimen.

RUN No. 6 Date: 20 April 1949

Type: Pure Compression

Axial Compressive Load (lbs)	Strain Gauge (micro-in.) Top of Plate	Bottom of Plate
136	- 46	- 43
220	- 80	- 70
304	- 108	- 90
404	- 159	- 110
472	- 202	- 115
552	- 277	- 98
572	- 301	- 81

RUN No. 7 Date: 21 April 1949

Type: Pure Shear

Shear Force Along Diag. (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
173	+ 38	+ 29
420	+ 86	+ 78
675	+ 134	+ 120
911	+ 178	+ 159
1220	+ 211	+ 188
1550	+ 252	+ 220
1895	+ 281	+ 229
2015	+ 297	+ 228
2115	+ 301	+ 210
2225	+ 329	+ 201
2285	+ 334	+ 199

Specimen: Plate No. 2 Plate thickness: 0.033 inches

Conditions: The same as Run No. 6.

RUN No. 8 Date: 21 April 1949

Type: Combined Compression and Shear. Constant shear force along the diagonal 286 pounds.

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
136	+ 6	- 1
224	- 19	- 22
312	- 51	- 40
356	- 79	- 54
436	- 119	- 61
540	- 187	- 44
612	- 269	+ 26

RUN No. 9 Date: 21 April 1949

Type: Combined Compression and Shear. Constant shear force along the diagonal 635 pounds.

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
64	+ 39	+ 28
156	+ 11	+ 7
220	- 8	- 16
316	- 38	- 39
384	- 61	- 61
468	- 87	- 73
500	- 92	- 79
540	- 110	- 85
600	- 138	- 100
636	- 156	- 102
684	- 184	- 102
708	- 200	- 100
740	- 228	- 90

Specimen: Plate No. 2 Plate thickness: 0.033 inches

Conditions: The same as Run No. 6.

RUN No. 10 Date: 21 April 1949

Type: Combined Compression and Shear. Constant shear force along the diagonal 1015 pounds.

Axial Compressive Load (lbs)	Strain Gauges(micro-in.) Top of Plate	Bottom of Plate
8	+ 56	+ 41
164	+ 25	+ 9
236	+ 5	- 9
332	- 33	- 45
396	- 53	- 58
472	- 64	- 68
532	- 78	- 78
600	- 94	- 89
624	- 103	- 97
664	- 113	- 104
720	- 135	- 117
752	- 143	- 121
768	- 154	- 127
824	- 175	- 139
868	- 193	- 141
900	- 206	- 147
940	- 226	- 140
972	- 254	- 107

Specimen: Plate No. 3 Plate thickness: 0.053 inches

Conditions: Lateral supports of cross section 3/16 inch by 1 inch, bolt holes 11/64 inch diameter, lateral supports and plate specimen joined by 8-32 size screws, finger tight. Shear force attachments connected to the plate specimen.

RUN No. 11 Date: 27 April 1949

Type: Pure Compression

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
122	- 36	- 29
198	- 69	- 41
314	- 118	- 52
370	- 152	- 40
394	- 168	- 30

RUN No. 12 Date: 27 April 1949

Type: Pure Compression

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
136	- 38	- 31
208	- 70	- 42
324	- 120	- 50
376	- 127	- 41
424	- 162	- 29

Specimen: Plate No. 3 Plate thickness: 0.033 inches

Conditions: The same as Run No. 11.

RUN No. 13 Date: 27 April 1949

Type: Pure Shear

Shear Force Along Diag. (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
45	+ 1	0
91	- 18	- 10
228	- 53	- 34
237	- 65	- 36
282	- 79	- 38
310	- 91	- 38
337	- 110	- 38
365	- 135	- 27
410	- 161	- 10

RUN No. 14 Date: 27 April 1949

Type: Combined Compression and Shear. Constant shear force along the diagonal 27 pounds

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
132	- 45	- 28
214	- 81	- 39
296	- 118	- 37
336	- 140	- 29

RUN No. 15 Date: 27 April 1949

Type: Combined Compression and Shear. Constant shear force along the diagonal 118 pounds.

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
142	- 99	- 70
172	- 111	- 73
214	- 132	- 69
236	- 146	- 68

RUN No. 16 Date: 27 April 1949

Type: Combined Compression and Shear. Constant shear force along the diagonal 246 pounds.

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
66	- 51	- 21
104	- 68	- 21
142	- 89	- 17
166	- 99	- 14

Specimen: Plate No. 4 Plate thickness: 0.0395 inches

Conditions: Lateral supports of cross section 3/16 inch by 1 inch, bolt holes 11/64 inch diameter, lateral supports and plate specimen joined by 8-32 size screws, finger tight. Shear force attachments connected to the plate specimen.

RUN No. 17 Date: 30 April 1949

Type: Pure Compression

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
112	- 21	- 30
192	- 41	- 59
276	- 49	- 98
312	- 47	- 121
352	- 38	- 150
400	- 22	- 181

RUN No. 18 Date: 30 April 1949

Type: Combined Compression and Shear. Constant shear force along the diagonal 191 pounds.

Axial Compressive Load (lbs)	Strain Gauges (micro-in.)	
	Top of Plate	Bottom of Plate
0	- 10	- 1
88	- 22	- 22
112	- 29	- 44
164	- 21	- 80
192	- 10	- 101

RUN No. 19 Date: 30 April 1949

Type: Combined Compression and Shear. Constant shear force along the diagonal 392 pounds.

Axial Compressive Load (lbs)	Strain Gauges (micro-in.)	
	Top of Plate	Bottom of Plate
0	+ 17	+ 22
48	+ 10	+ 13
96	+ 8	- 4
132	+ 2	- 18
172	+ 1	- 36
204	+ 6	- 65

Specimen: Plate No. 4 Plate thickness: 0.0395 inches

Conditions: The same as Run No. 17.

RUN No. 20 Date: 30 April 1949

Type: Combined Compression and Shear. Constant shear force along the diagonal 630 pounds.

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
0	+ 2	+ 11
84	- 11	- 10
132	- 22	- 29
164	- 31	- 38
200	- 32	- 49
244	- 31	- 68
264	- 29	- 79

RUN No. 21 Date: 30 April 1949

Type: Combined Compression and Shear. Constant shear force along the diagonal 875 pounds.

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
0	- 11	- 11
104	- 31	- 29
144	- 42	- 34
184	- 55	- 38
224	- 70	- 47
276	- 73	- 54
304	- 74	- 59
328	- 80	- 58
364	- 72	- 68
392	- 53	- 88
420	+ 17	- 158

Specimen: Plate No. 5 Plate thickness: 0.064 inches

Conditions: Lateral supports of cross section 3/16 inch by 1 inch, bolt holes 11/64 inch diameter, lateral supports and plate specimen joined by 8-32 size screws, finger tight. Shear force attachments connected to plate specimen.

RUN No. 22 Date: 3 May 1949

Type: Pure Compression

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
172	- 31	- 25
272	- 50	- 43
376	- 68	- 58
504	- 90	- 76
568	- 103	- 85
680	- 125	- 103
772	- 143	- 114
872	- 156	- 123
972	- 170	- 132
1072	- 189	- 136
1172	- 200	- 143
1272	- 213	- 144
1352	- 224	- 148
1460	- 240	- 144
1548	- 250	- 143
1580	- 251	- 143
1620	- 254	- 142
1632	- 259	- 142

RUN No. 23 Date: 4 May 1949

Type: Combined Compression and Shear. Constant shear force along the diagonal 474 pounds.

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
0	- 71	- 57
268	- 133	- 79
460	- 170	- 88
668	- 211	- 102
852	- 245	- 114
1052	- 275	- 123
1256	- 311	- 131
1296	- 316	- 130
1416	- 324	- 129
1456	- 332	- 128
1492	- 334	- 127

Specimen: Plate No. 5   Plate thickness: 0.064 inches

Conditions: The same as Run No. 22

RUN No. 24 Date: 4 May 1949

Type: Combined Compression and Shear. Constant shear force along the diagonal 1010 pounds.

RUN No. 25 Date: 4 May 1949

Type: Combined Compression and Shear. Constant shear force along the diagonal 1660 pounds.

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate	Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
0	- 71	- 18	0	- 99	+ 6
280	- 143	- 47	492	- 215	- 20
456	- 180	- 61	700	- 251	- 26
680	- 222	- 78	876	- 279	- 26
868	- 257	- 87	920	- 281	- 26
1068	- 287	- 88	960	- 285	- 26
1264	- 303	- 87	1000	- 291	- 25
1344	- 310	- 85	1036	- 293	- 25

Specimen: Plate No. 6 Plate thickness: 0.065 inches.

Conditions: Lateral supports of cross section 3/16 inch by 1 inch, bolt holes 11/64 inch diameter, lateral supports and plate specimen joined by 8-32 size screws, finger tight. Shear force attachments connected to plate specimen on each side by Pins III and IV only.

RUN No. 26 Date: 5 May 1949

Type: Pure Compression

Axial Compressive Load (lbs)	Strain Gauges (micro-in.)	
	Top of Plate	Bottom of Plate
260	- 46	- 40
664	- 123	- 82
860	- 154	- 92
1064	- 191	- 99
1240	- 220	- 101
1336	- 233	- 101
1408	- 241	- 99
1444	- 243	- 98

Specimen: Plate No. 6 Plate thickness: 0.065 inches.

Conditions: The same as Run No. 26

RUN No. 27 Date: 5 May 1949

Type: Combined Compression and Sheer. Constent shear force along the diagonal 474 pounds.

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
0	- 39	- 11
316	- 115	- 48
704	- 207	- 73
1000	- 263	- 89
1128	- 275	- 96
1216	- 282	- 96
1252	- 287	- 96
1300	- 289	- 93

RUN No. 28 Date: 5 May 1949

Type: Combined Compression and Sheer. Constant shear force along the diagonal 1067 pounds.

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
0	- 70	- 31
312	- 152	- 40
512	- 201	- 49
700	- 239	- 61
904	- 276	- 69
1024	- 292	- 70
1048	- 297	- 71
1096	- 301	- 72
1132	- 302	- 75
1176	- 306	- 76
1212	- 310	- 77
1260	- 311	- 77
1288	- 311	- 76
1340	- 316	- 76

Specimen: Plate No. 6 Plate thickness: 0.065 inches

Conditions: The same as Run No. 26

RUN No. 29 Date: 6 May 1949

Type: Combined Compression and Shear. Constant shear force along the diagonal 530 pounds.

RUN No. 30 Date: 6 May 1949

Type: Combined Compression and Shear. Constant shear force along the diagonal 1110 pounds.

Run No. 29: Axial Compressive Load (lbs)	Strain Gauge (micro-in.) Top of Plate	Strain Gauge (micro-in.) Bottom of Plate	Run No. 30: Axial Compressive Load (lbs)	Strain Gauge (micro-in.) Top of Plate	Strain Gauge (micro-in.) Bottom of Plate
0	- 59	- 36	0	- 98	- 25
296	- 120	- 64	364	- 184	- 43
492	- 160	- 90	492	- 210	- 50
704	- 207	- 111	588	- 235	- 52
900	- 248	- 126	680	- 249	- 59
1012	- 267	- 140	764	- 260	- 60
1096	- 273	- 142	840	- 261	- 61
1132	- 277	- 143	924	- 281	- 64
1168	- 280	- 143	1000	- 290	- 69
1204	- 285	- 146	1084	- 300	- 69
1256	- 289	- 144	1160	- 306	- 69
1296	- 288	- 144	1200	- 308	- 69
1364	- 294	- 143	1280	- 312	- 69
1412	- 298	- 142	1324	- 317	- 69

Specimen: Plate No. 7 Plate thickness: 0.030 inches

Conditions: Lateral supports of cross section 3/16 inch by 1 inch, bolt holes 11/64 inch diameter, lateral supports and plate specimen joined by 8-32 size screws, finger tight. Shear force attachments connected to plate specimen on each side by Pins III and IV only.

RUN No. 31 Date: 6 May 1949

Type: Pure Compression

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
60	- 23	- 17
136	- 59	- 32
216	- 108	- 46
296	- 158	- 37
336	- 187	- 27
384	- 223	- 6

RUN No. 32 Date: 6 May 1949

Type: Pure Compression

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
60	- 23	- 19
100	- 41	- 26
140	- 61	- 37
176	- 85	- 40
220	- 110	- 42
264	- 141	- 40
308	- 170	- 32
336	- 200	- 22

RUN No. 33 Date: 6 May 1949

Type: Combined Compression and Shear. Constant shear force along the diagonal 19 pounds.

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
0	- 16	- 18
112	- 71	- 49
184	- 111	- 53
272	- 171	- 45

RUN No. 34 Date: 6 May 1949

Type: Combined Compression and Shear. Constant shear force along the diagonal 57 pounds.

Axial Compressive Load (lbs)	Strain Gauges (micro-in.) Top of Plate	Bottom of Plate
0	- 3	1
56	- 22	- 13
96	- 38	- 24
132	- 58	- 31
180	- 87	- 37
216	- 112	- 38

APPENDIX D

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